AD/A-000 939

CATALYTIC REACTOR FOR INERTING OF AIRCRAFT FUEL TANKS

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AiResearch Manufacturing Company

Prepared for:

Air Force Aero Propulsion Laboratory

June 1974

UNCLASSIFIED
Security Classification

AD/A-000939

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
AiResearch Manufacturing Company
2525 West 190th Street
Torrance, California

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
CATALYTIC REACTOR FOR INERTING OF AIRCRAFT FUEL TANKS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report - June 1971 to June 1974

5. AUTHOR(S) *(First name, middle initial, last name)*
J. Rousseau
G. H. McDonald

6. REPORT DATE
June 1974

7a. TOTAL NO. OF PAGES
109

7b. NO. OF REFS
2

8a. CONTRACT OR GRANT NO.
F33615-71C-1901

b. PROJECT NO.
3048

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
74-10294

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
AFAPL-TR-74-49

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Air Force Aero Propulsion Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

13. ABSTRACT

This program, Catalytic Reactor for Inerting of Aircraft Fuel Tanks, was concerned with the development of a prototype catalytic reactor for the generation of inert gases through jet fuel combustion in engine bleed air. Successful operation of a flight-configured unit was achieved at very high effectiveness. Inert gas oxygen concentrations below 1 percent were achieved repeatedly. Design data were generated related to reactor performance under various operating conditions and also related to thermal and mechanical design of the unit. Corrosion testing of aircraft fuel tank construction materials including metals, coatings, and sealants was conducted. These materials were evaluated in terms of resistance to corrosion by SO_2 formed in the fuel oxidation reactor. Using the experimental data generated under this program, a complete fuel tank inerting system was synthesized. This system weighs 305 lb, has an overall envelope of 19 by 24 by 55 in., and satisfies all flight conditions including emergency descent of a large-volume bomber-type of aircraft.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fuel Tank Inerting						
Catalytic Fuel Oxidation						

UNCLASSIFIED
Security Classification

*U.S.Government Printing Office: 1974 — 657-015/192

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AIR FORCE/56780/8 November 1974 — 100

FOREWORD

This program, Catalytic Reactor for Inerting of Aircraft Fuel Tanks, was conducted by the AiResearch Manufacturing Company of Los Angeles, a division of The Garrett Corporation, under USAF Contract F33615-71C-1901. The work was sponsored and administered by the Air Force Aero Propulsion Laboratory under Air Force Project 3048, Task 304807, Work Unit 30480739. Gregory Gandee (SFH) was the USAF project engineer.

The period of performance extended from June 29, 1971 to June 1, 1974. Mr. George H. McDonald of AiResearch was the program manager and project engineer. Other AiResearch personnel who made significant contributions include P. Friedel, D. Graumann, G. E. Limberg, J. Rousseau, and H. G. Starck.

This technical report has been assigned AiResearch report No. 74-10294. This report was submitted by the authors in June, 1974.

This technical report has been reviewed and is approved.

Benito P. Botteri

Benito P. Botteri
Chief, Fire Protection Branch
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SECTION I

INTRODUCTION AND SUMMARY

1. GENERAL

This document summarizes the results of a program concerned with the development of an advanced combustion technique for aircraft fuel tank inerting. The source of inert gas is engine bleed air depleted of oxygen by low-temperature oxidation of jet fuel in a thermally controlled catalytic reactor.

Previous work concerned with the development of this process was performed under USAF Contracts F33615-68-C-1500, F33615-70-C-1492, and F33615-70-C-1616, by American Cyanamid Company, AiResearch, and Hamilton Standard Division of United Aircraft. This work was involved with catalyst screening and selection, and preliminary system design studies.

At the start of this program, process feasibility had been demonstrated as a result of catalyst investigations conducted by American Cyanamid Company and AiResearch. The potential effectiveness of the American Cyanamid Code A catalyst to promote the low-temperature fuel oxidation reaction had been established. System analysis and integration had shown that an aircraft fuel tank inerting system based on catalytic fuel combustion offered many advantages over competing approaches in terms of weight and logistics requirements.

The program described in this report covered this developmental area concerned with the resolution of intricate process and hardware problems which arise in the translation of test tube technology into flight prototype equipment.

The major objectives of the program were to:

a. Develop design specifications for a combustion inerting system for a large bomber-type of aircraft.

b. Develop preliminary system designs for an inerting system tailored to the typical large bomber aircraft requirements.

c. Develop breadboard equipment scaled to the requirements of the aircraft.

d. Identify potential material problems due to corrosive products formed as a result of fuel oxidation.

2. PROGRAM SCOPE

The program covered a period of thirty-six months. Activities were oriented toward the accomplishment of the program objectives listed above.

A design specification was developed for a fuel oxidation inerting system for the aircraft. This specification is contained in an AiResearch report submitted to the Air Force earlier in the program.

The major portion of the effort was devoted to the development of a prototype reactor of a configuration suitable for flight. This involved resolution of process and hardware problems, many of which were identified as the program proceeded. This extensive test program involved four different reactors and a complete breadboard system scaled to the bomber fuel tank inert gas requirements. The results of this phase of the program are reported in Section III.

As part of the reactor development, contaminants produced in the fuel oxidation process were identified. A comprehensive material corrosion test program was conducted. This program covered metals commonly used in fuel tank construction and coating and sealant materials currently used for corrosion protection. A summary of this corrosion test program is presented in Section IV.

Analytical efforts concerned with system definition were initiated early in the program to provide system data that could be used for the purpose of system level trade studies, and also for planning and designing the breadboard reactors and system development program. These data were updated as developmental data became available. The final inerting system configuration recommended is described in Section V.

3. PROGRAM ACHIEVEMENTS

The program described herein was eminently successful in meeting all objectives. Major program achievements are presented below in terms of these objectives.

a. Design Specifications

As mentioned earlier, a fuel tank inerting system specification based on fuel oxidation was prepared and submitted to the Air Force in AiResearch Report No. 71-7829.

b. Breadboard Development

A prototype catalytic reactor of a configuration suitable for flight was successfully developed. This reactor was operated at an inert gas output of 1 lb/min with an oxygen concentration as low as 0.5 percent (average between 1 and 2 percent). Major achievements include:

(1) High oxidation reaction effectiveness

(2) Stability of operation

(3) Effective thermal control

(4) Verification of the configuration and construction in simulated aircraft operating conditions

(5) Generation of design data covering a wide range of operating parameters

c. Material Corrosion

Analysis of the inert gas composition revealed that the water condensed from the inert gas stream was very acidic (pH as low as 1.9). This establishes a requirement for a sorbent bed downstream of the reactor to prevent corrosion of system equipment and of the fuel tanks.

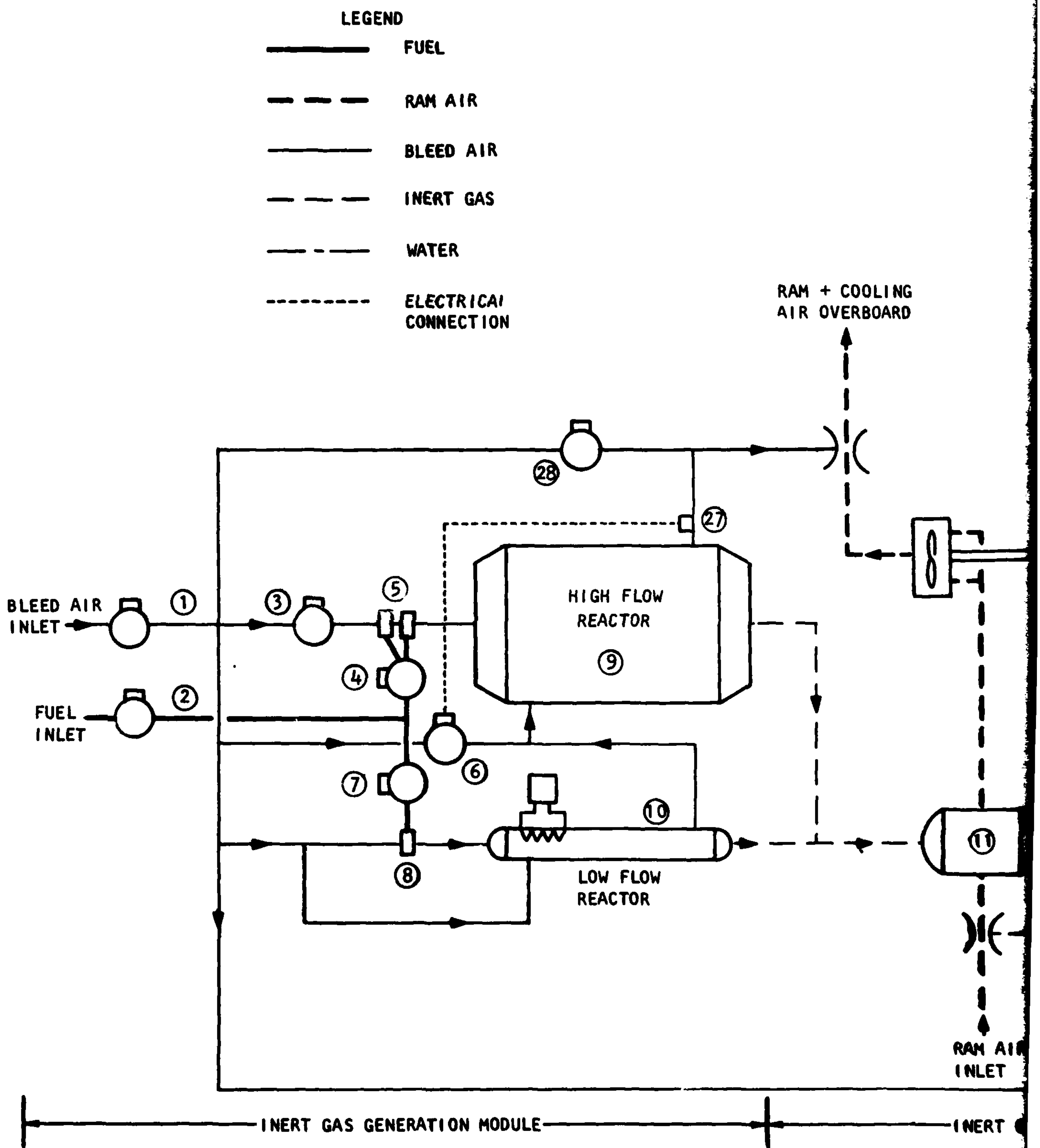
Tests performed on metals used in the construction of fuel tanks resulted in heavy corrosion of all materials investigated (except for titanium) when exposed to an aqueous solution of SO_2. State-of-the-art sealant and coating materials showed good corrosion resistance.

d. Preliminary System Design

A fuel tank inerting system was synthesized to meet all flight requirements including emergency descent. A schematic of the system is shown in Figure 1. The system package is presented as Figure 2. System overall characteristics are as follows:

Overall weight:	305 lb including internal ducts and structure
Package envelope	19 by 24 by 55 in.
Inert gas generation rate	• 0.5 lb/min at 0.7 percent O_2 concentration • 33 lb/min at 2.0 percent O_2 concentration • 52 lb/min at 9 percent O_2 concentration • 106 lb/min at 12.0 percent O_2 concentration
Controls	Fully automatic except for startup and sparging
Life	4000 hr; 500 hr between servicing

A


LEGEND
FUEL
RAM AIR
BLEED AIR
INERT GAS
WATER
ELECTRICAl CONNECTION
RAM + COOLING AIR OVERBOARD
BLEED AIR INLET
FUEL INLET
HIGH FLOW REACTOR
LOW FLOW REACTOR
RAM AI
INLET
INERT GAS GENERATION MODULE
INERT
1
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27
28

B

1. BLEED-AIR SUPPLY SHUTOFF VALVE
2. FUEL SHUTOFF VALVE
3. HIGH-FLOW MODE BLEED SHUTOFF
4. HIGH-FLOW MODE FUEL SHUTOFF VALVE
5. HIGH-FLOW FUEL NOZZLES
6. REACTOR TEMPERATURE CONTROL VALVE
7. LOW-FLOW MODE FUEL SHUTOFF VALVE
8. LOW-FLOW FUEL NOZZLE
9. HIGH-FLOW REACTOR
10. LOW-FLOW REACTOR
11. COOLER-CONDENSER
12. COOLING TURBINE FAN ASSEMBLY
13. MODE CONTROL VALVE
14. TURBINE BYPASS CONTROL
15. WATER SEPARATOR - TURBINE OUTLET
16. HIGH-FLOW DUMP VALVE
17. HIGH-FLOW BLEED MAKEUP
18. EMERGENCY BLEED-AIR INFLOW VALVE
19. TEMPERATURE SENSOR
20. FUEL COOLER
21. FUEL BYPASS VALVE
22. TEMPERATURE SENSOR
23. WATER SEPARATOR
24. LOW-FLOW DUMP VALVE
25. LOW-FLOW BLEED MAKEUP
26. INERT GAS FILTER
27. TEMPERATURE SENSOR
28. BLEED AIR SHUTOFF VALVE

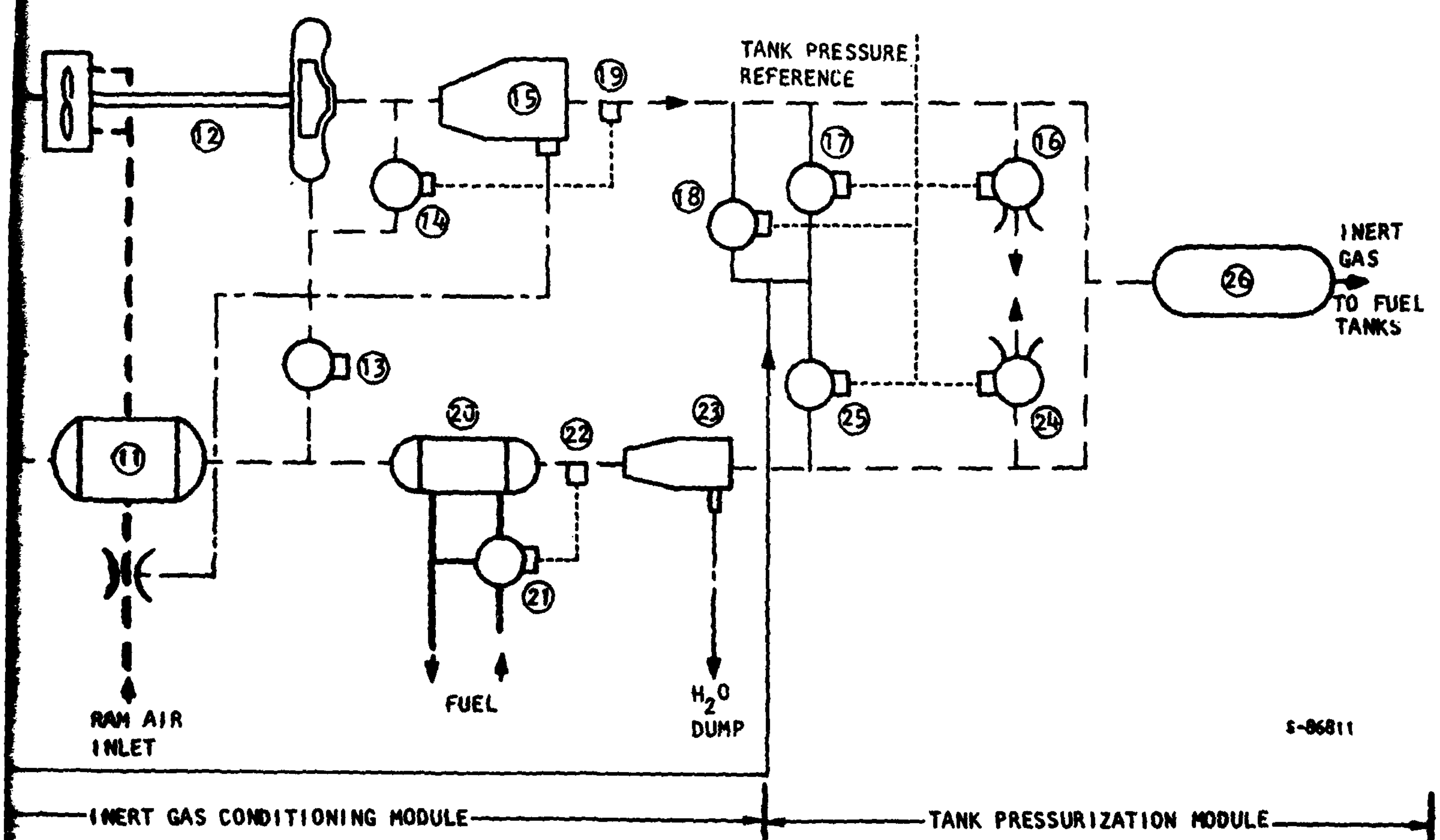

Figure 1. System Schematic

A

1. BLEED-AIR SUPPLY SHUTOFF VALVE
2. FUEL SHUTOFF VALVE
3. HIGH-FLOW MODE BLEED SHUTOFF
4. HIGH-FLOW MODE FUEL SHUTOFF VALVE
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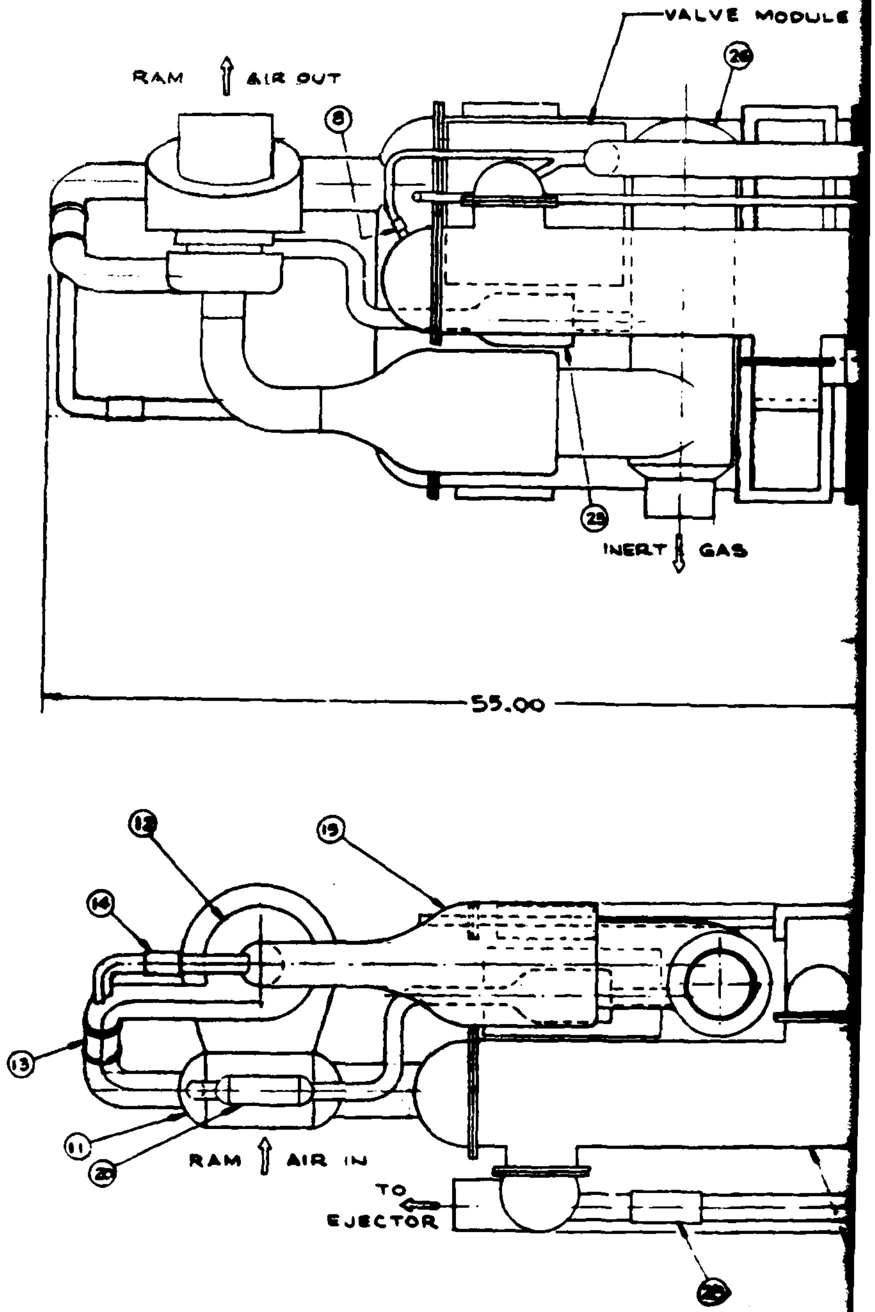
27. TEMPERATURE SENSOR
28. BLEED AIR SHUTOFF VALVE



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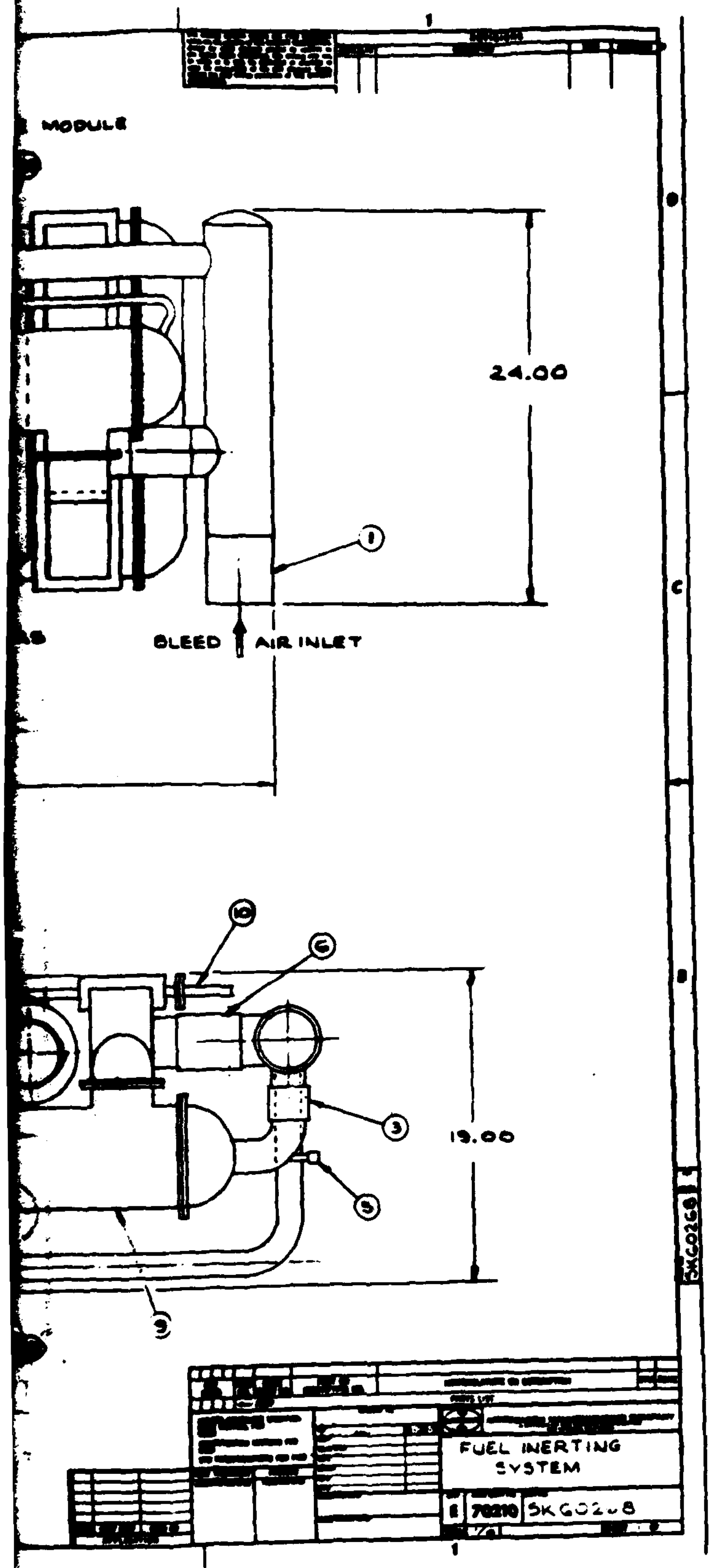

Figure 2. Equipment Arrangement

SECTION II

SYSTEM DESIGN REQUIREMENTS

1. GENERAL

The inerting system requirements were established to maintain noncombustible tank ullage during all portions of the aircraft mission. A typical mission was used to define the tank inerting system interface and flow requirements.

2. PERFORMANCE REQUIREMENTS

a. Flow Rate

Figure 3 shows the inert gas flow profile for a typical mission. The estimated entire weight of inert gas delivered to the tank over the mission is 534 lb. Of this, only a small amount (43 lb) is necessary for normal climb-and-cruise operations. By far, the largest portion of the inert gas is used for sparging after fueling (180 lb) and for tank pressurization during descent (266 lb).

Figure 4 is a plot of inert gas flow required to maintain tank pressure during maximum normal descent and emergency descent. The emergency descent flow was established on the requirement for tank pressurization from an altitude of 39, 000 feet with 20-percent fuel remaining in the tanks.

Pertinent inert gas flow rates are listed below in terms of aircraft operating modes:

Normal operations	Less than 0.5 lb/min
Fuel tank sparging	15 lb/min
Normal maximum descent	52 lb min
Emergency descent	106 lb/min

b. Inert Gas Composition

(1) Oxygen Content

The inerting system is designed to deliver to the fuel tank a noncombustible mixture of nitrogen, carbon dioxide, and oxygen (plus trace amounts of other constituents) under all aircraft modes of operation. The maximum oxygen content specified for the inert gas depends on the mission mode as defined in Table I.

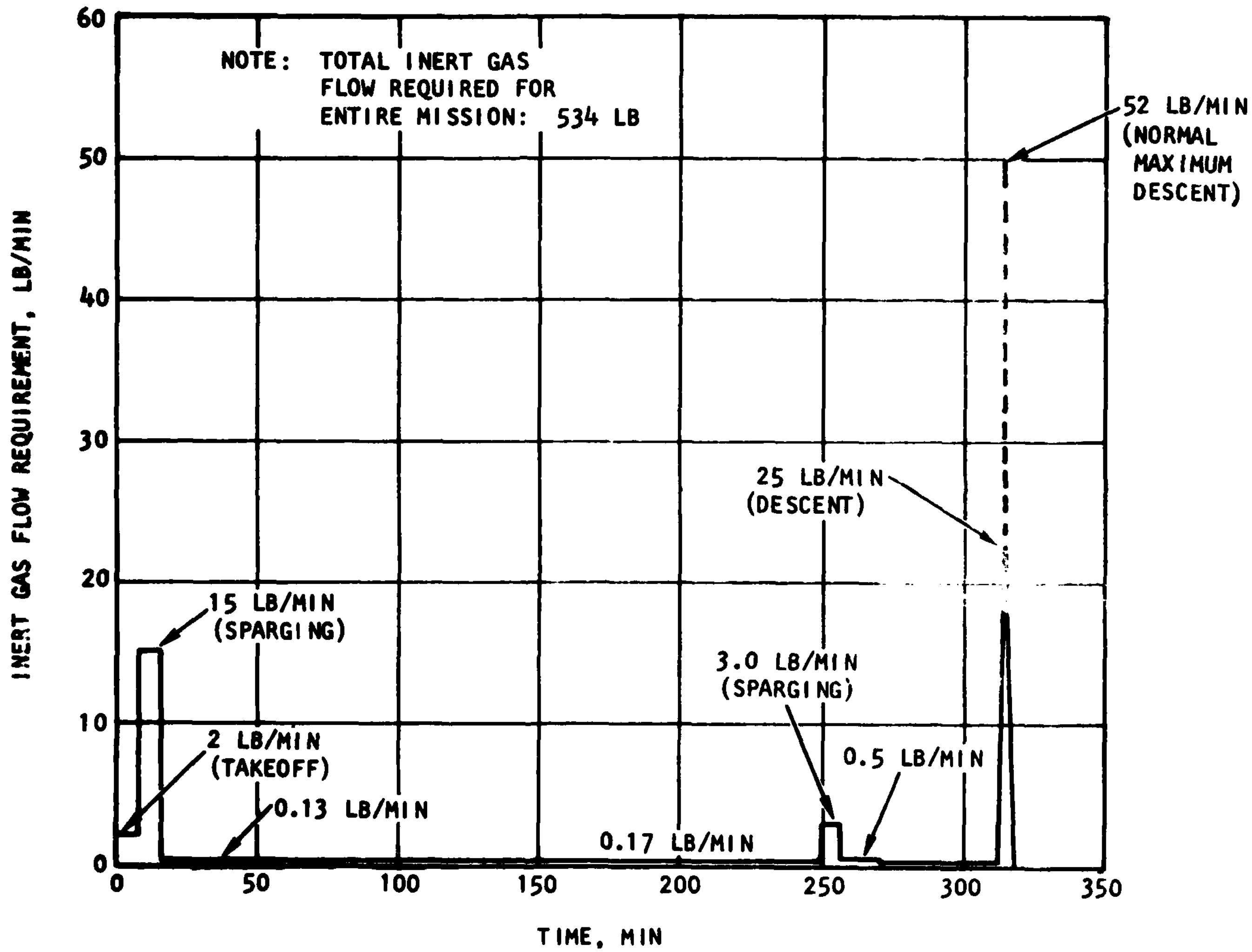

Figure 3. Inert Gas System Flow Requirement

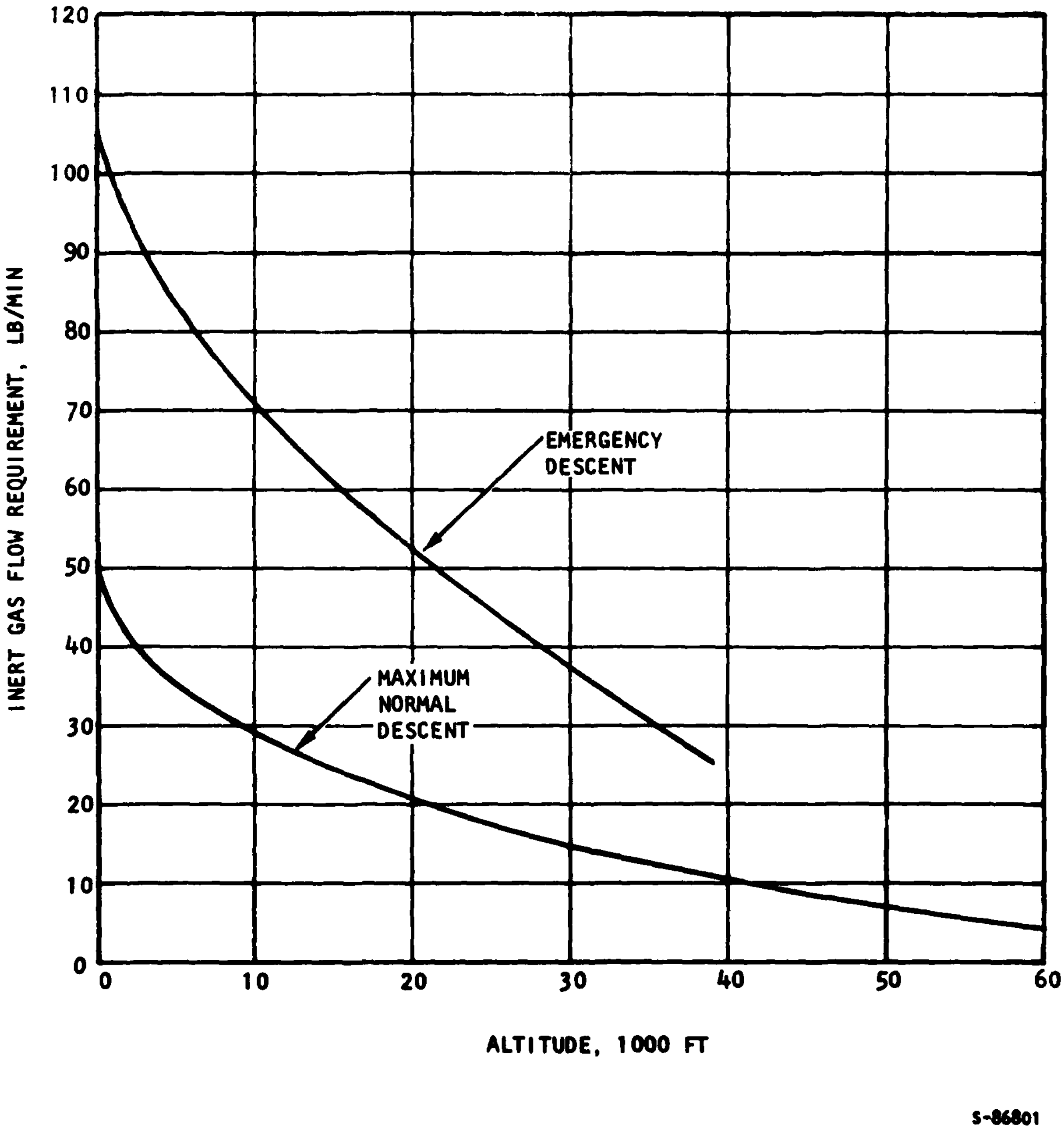

Figure 4. Fuel Tank Flow Requirements During Descent

TABLE I

MAXIMUM INERT GAS O_2 CONTENT

Operating Mode	Maximum O_2 Concentration in Inert Gas, percent volume
Normal (All operations except climb)	9
Sparging (during climb)	2-5
Ground	9
Emergency descent	11-12

As shown, the maximum inert gas O_2 content is 9 percent by volume, except during emergency descent and during sparging.

The inert gas flow to the fuel tank during climb will be adequate to sparge oxygen released from the fuel as tank pressure decreases with altitude. The low oxygen content of the sparge is essential under this mode of operation to prevent O_2 concentration buildup above 9 percent. Sparging is necessary only during initial climbs to any new altitude from a lower level. The requirement for sparging also exists after inflight refueling.

(2) Moisture Content

Over the average aircraft mission, the average moisture content of the inert gas delivered to the tanks will be maintained below 30 gr/lb of gas. This requirement is waived for emergency descent. The moisture level design goal is 15 gr/lb of gas.

(3) Inert Gas Contaminants

Catalytic oxidation of jet fuel at low temperature will generate undesirable products due to (1) the composition of the fuel, and (2) ineffectiveness of the combustion process.

Sulfur compounds contained in the fuel will be oxidized to SO_2, which is highly corrosive. Provisions must be made for the removal of this compound immediately downstream of the catalytic reactor to prevent entrainment and damage to the inerting system equipment and the fuel tanks. The maximum sulfur content of jet fuel is 0.15 percent by weight.

Incomplete fuel combustion will result in the formation of tars and carbon that could accumulate in the inerting system equipment and also could be entrained to the fuel tanks. Filters must be incorporated in the system design to guard against contamination by tars and carbon.

c. Inert Gas Temperature

The maximum temperature of the inert gas delivered to the fuel tank will be 200°F under all operational modes except emergency descent when the maximum allowable temperature is 325°F. Design goal is 100°F.

d. Fuel

The fuel tank inerting system will be capable of normal operation on any of the following fuels: JP-4, JP-5, and JP-8. In an emergency, system operation with automotive gasoline will be possible. The maximum sulfur content of the fuel is 0.15 percent.

3. DESIGN REQUIREMENTS

a. Weight Limitations

The maximum specific weight of the system is specified at 15 lb/(lb/min) of inert gas delivered to the tank under maximum normal flow. Referring to Figure 4, the maximum allowable system weight is 780 lb for a normal maximum flow of 52 lb/min.

The system specific weight goal is 8 lb/(lb/min) inert gas for a total system weight of 416 lb. These weights do not include air, inert gas, or fuel ducts and lines to and from the inerting system package.

b. Controls

System controls will be automatic and will require minimal crew attention. Overrides and/or resets will be provided for operations such as sparging. Warnings on the control panel will alert the crew to system malfunction.

c. Life and Maintenance Period

The minimum design life of the system is 4000 hr. The minimum time period specified for servicing and replacement of catalyst beds, filters, and sorbent beds is 500 hr.

SECTION III

REACTOR AND SYSTEM DEVELOPMENT

1. GENERAL

The catalytic reactor was identified as the critical component in terms of development risks early in the program. Previous work by American Cyanamid Company[1] and AiResearch Manufacturing Company[2] demonstrated the effectiveness of the American Cyanamid Company Code A catalyst for relatively low-temperature oxidation of common aircraft fuels. As a consequence, this catalyst was selected as baseline.

The problems associated with the design and development of a reactor suitable for aircraft operation are related to temperature control of the catalyst bed for:

- High catalyst activity--Low temperatures (400°F) due to overcooling will quench the reaction while high temperatures (1500°F) will adversely affect catalyst activity.

- Structural integrity--Construction materials and techniques impose an upper-temperature limit of about 1300°F for long-term cyclic operation. Also, uniform temperature along and across the reactor is desirable to obviate excessive thermal stresses.

Recognizing these problems and the lack of engineering data to predict local fuel oxidation rates and exothermic heat generation within a reactor of flight configuration, the decision was made early in the program to design and build a laboratory test unit for the purpose of gathering design data.

The general objectives of the test program were (1) to determine the effect of operating parameters on reactor effectiveness, and (2) to validate the basic concept used in the design of the laboratory unit to achieve the desired thermal performance. Specifically, the test program was designed to provide the following information:

Effect of bleed-air inlet temperature, pressure, and flow rate

Effect of cooling-air inlet temperature and flow rate

Effect of fuel-air ratio on inert gas composition

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(1) Wainright, R. B., and A. Perlmutter, Generation of Inerting Gases for Aircraft Fuel Tanks by Catalytic Combustion Techniques, AFAPL-TR-69-68, American Cyanamid Company, August 1969.

(2) Hamilton, MacKenzie, L., Aircraft Fuel Tank Inerting Program, AFAPL-TR-70-83, AiResearch Manufacturing Company, Los Angeles, January 1971.

Cooling air effectiveness

Metal temperature along the reactor

As a parallel effort, a breadboard fuel tank inerting system was designed to demonstrate system function and performance under a variety of steady state and transient operating conditions. The breadboard system featured two reactors: (1) a 1-lb/min unit adequate for fuel tank pressurization under most mission phases, and (2) a 6.0-lb/min unit approximating a 1/8-scale version of the high-flow unit designed to satisfy the flow requirements of the maximum normal descent conditions.

While system design and assembly was conducted concurrently with testing of the laboratory reactor, the 1- and 6-lb/min reactors were only designed and fabricated after sufficient data were obtained on the laboratory reactor.

As discussed later, exploratory system development efforts were hampered by reactor problems related to reaction stability. Consequently, the decision was made to divert the entire developmental effort to the resolution of these problems. This phase of the program involved development of the following:

Reactor recirculation loop

Flame arrestor

A 1-lb/min reactor to be used as the prototype module

2. LABORATORY REACTOR DEVELOPMENT PROGRAM

a. Laboratory Reactor Description

The test unit was designed for inerting bleed air at a flow rate of 0.5 lb/min using American Cyanamid Code A catalyst. Temperature control is effected using a ram air source. Significant design parameters with the ranges covered during the test program are listed in Table II. In addition, the laboratory unit was designed for an approximate maximum metal temperature of 1300°F.

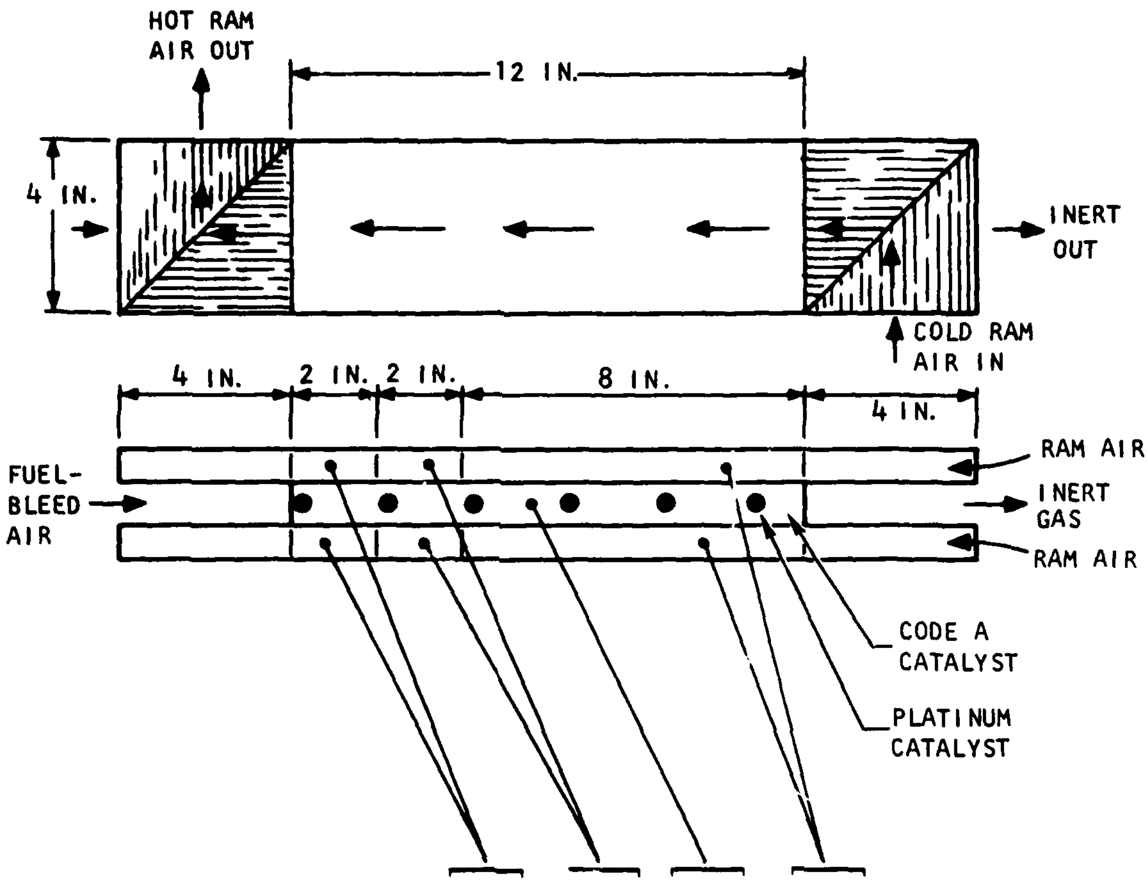
Figure 5 defines the pertinent reactor design features. Provisions are made for monitoring reactor wall temperatures at 28 locations in two parallel rows along the axis of the reactor. Figure 6 is a photograph showing the temperature instrumentation leads.

The reactor consists of a plate-fin counterflow heat exchanger with three passages. The center passage, 0.25 in. high by 3.8 in. wide by 12 in. long, contains the catalyst charge. The cooling ram air is circulated in finned passages on both sides of the catalyst charge.

TABLE II

LABORATORY REACTOR TEST PARAMETER RANGE

Parameter	Design Value	Test Range
Bleed Air		
Flow, lb/min	0.5	0.15 to 0.5
Inlet temperature, °F	500	200 to 700
Inlet pressure, psig	30	0 to 30
Ram Air		
Flow, lb/min	2.5	0.8 to 5.0
Inlet temperature, °F	225	100 to 640
Inlet pressure, psig		0 to 10
Fuel-Air Ratio		
lb fuel/lb air	0.068	0.06 to 0.34



FINS PER IN.	28	20	4	8
FIN HEIGHT, IN.	0.153	0.153	0.250	0.153
FIN OFFSET, IN.	0.100	0.125	---	0.125
FIN THICKNESS, IN.	0.006	0.006	0.004	0.006

FIN SECTION RECTANGULAR THROUGHOUT

- FLOW CONFIGURATION = COUNTERFLOW
- CATALYST: AMERICAN CYANAMID CODE A WITH PLATINUM COATED PELLETS AT 2-IN. INTERVALS IN THE FLOW DIRECTION
- PLATE FIN CONSTRUCTION WITH VARIABLE F'N DENSITY ON THE COOLANT SIDE
- REACTOR WALL TEMPERATURES MEASURED AT 28 LOCATIONS ALONG AXIS

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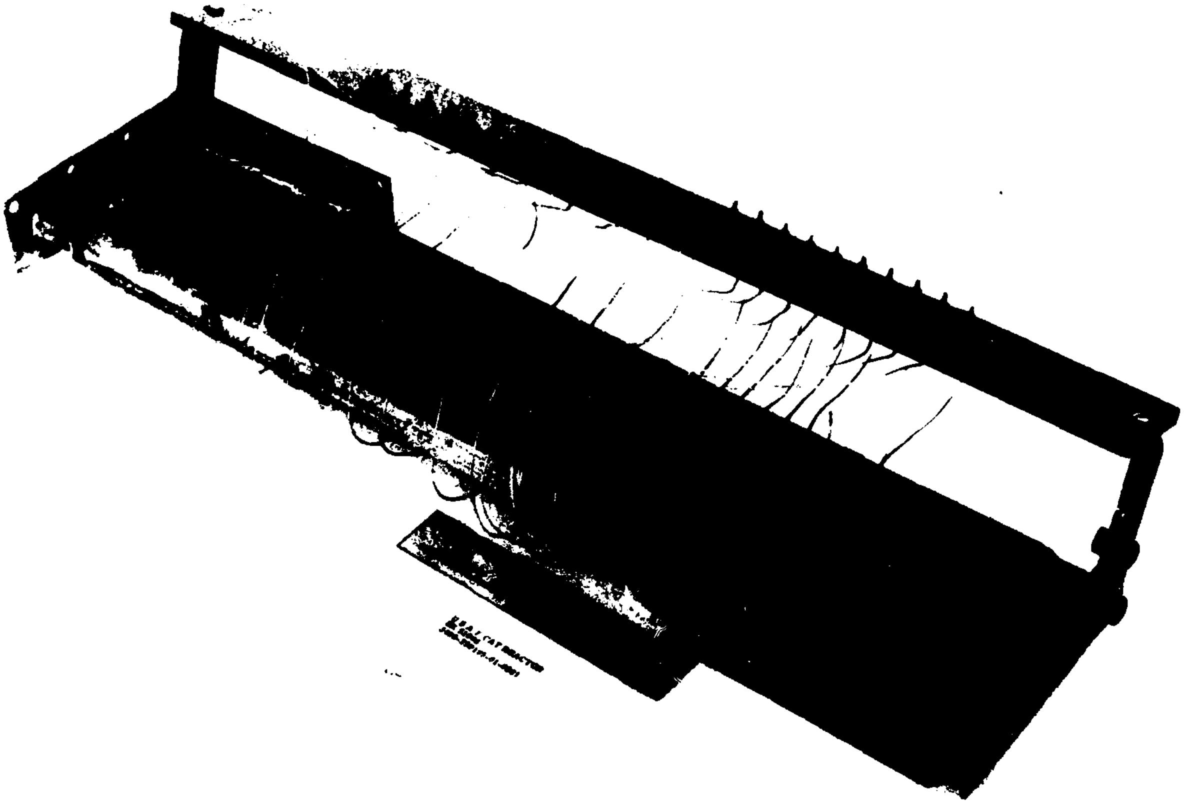
Figure 5. Laboratory Reactor Details



The density of the extended heat transfer surface within the cooling passages varies along the length of the passage to provide maximum heat-sink capability in the region where the reaction rates were expected to be the highest. In this manner, the temperature peak in the front of the reactor bed is minimized. A looser fin surface is used to cool the downstream portion of the reactor bed to prevent chilling of the bed and also to minimize ram-air pressure drop.

Platinum catalyst (platinum black on alumina) is loaded within the Code A catalyst passage at 2-1/8-in. intervals along the length of the bed to provide self-starting capabilities. The 1/4-in.-thick catalyst bed dimension was selected as a good compromise considering bed temperature control in the transverse direction and channelling effects due to the relatively small cross-sectional area (0.25 in. by 0.25 in.) of the passages formed by the rectangular fin. Note that the catalyst pellet size is about 0.1 in. dia by about 0.15 in. long, so that wall effects will be a significant factor in terms of reactor effectiveness.

The catalyst bed was sized to provide a space velocity of 18,000 hr^{-1}, which was found effective in early development work conducted by American Cyanamid Company for fuel tank inerting application.

Thermocouples at 28 locations along the reactor surface between the catalyst bed and the ram-air cooling passage determine accurately the metal temperature throughout the unit and thus provide experimental data for thermal and stress analysis of the prototype unit. Figure 7 shows the instrumented plate.

b. Laboratory Reactor Test Setup

A schematic of the experimental apparatus is presented in Figure 8 and a photograph of the test setup is shown as Figure 9. Prior to testing, all hot portions of the test rig were covered with a thick blanket of insulation to minimize the effects of heat leaks.

The test setup consists of the following three separate circuits:

(1) The fuel-feed circuit has valves and instruments for accurate control and monitoring of the fuel flow. The fuel tank is pressurized with nitrogen at about 300 psig from a 2000-psig gas bottle supply. Fuel flow is controlled by means of a manual metering valve. A solenoid valve in the fuel-feed line is shut off if the temperature in the bleed-air manifold exceeds 900°F. The fuel air mixture is fed to the reactor through a set of atomizing nozzles. Nitrogen lines are provided to purge the fuel feed system and reactor after each run.

(2) The bleed-air supply to the reactor is controlled by a throttle valve. An electrical heater in the bleed-air supply line provides the capability for heating to a temperature of 700°F. The pressure in the

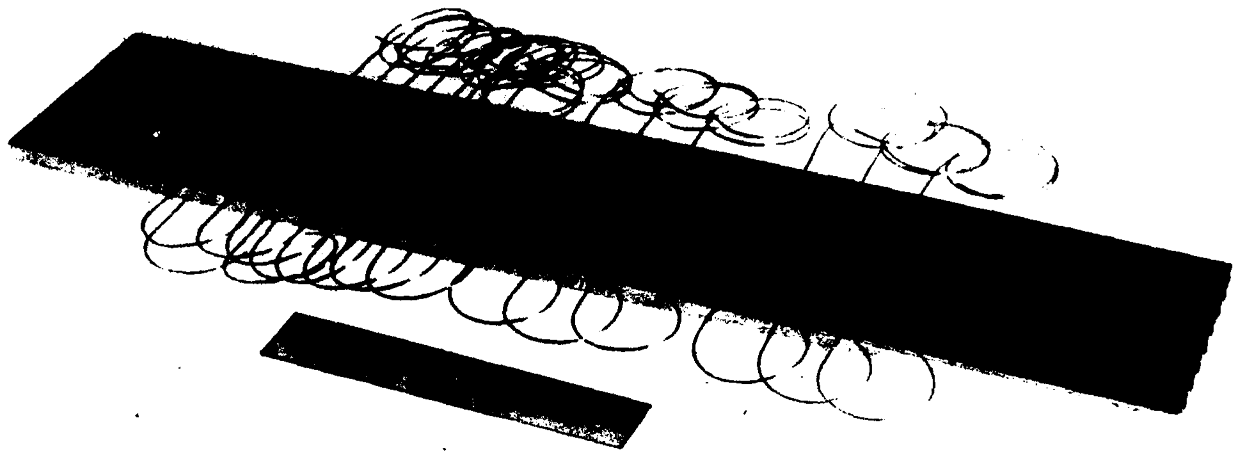
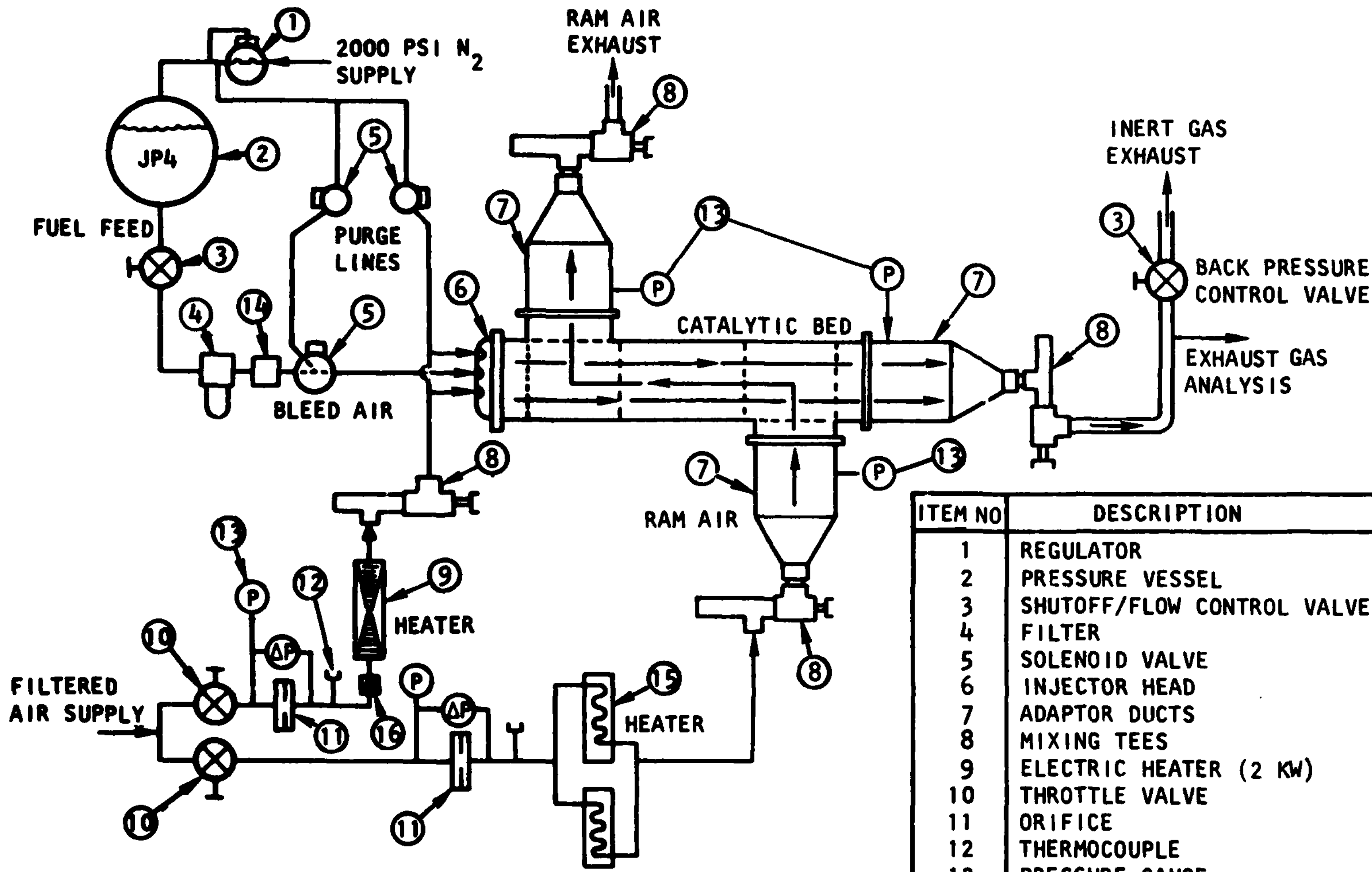


Figure 7. Laboratory Unit Thermocouple Installation



ITEM NO	DESCRIPTION
1	REGULATOR
2	PRESSURE VESSEL
3	SHUTOFF/FLOW CONTROL VALVE
4	FILTER
5	SOLENOID VALVE
6	INJECTOR HEAD
7	ADAPTOR DUCTS
8	MIXING TEES
9	ELECTRIC HEATER (2 KW)
10	THROTTLE VALVE
11	ORIFICE
12	THERMOCOUPLE
13	PRESSURE GAUGE
14	FLOWMETER
15	ELECTRIC HEATER (12 KW)
16	CHECK VALVE

S-86808

Figure 8. Laboratory Reactor Test Setup

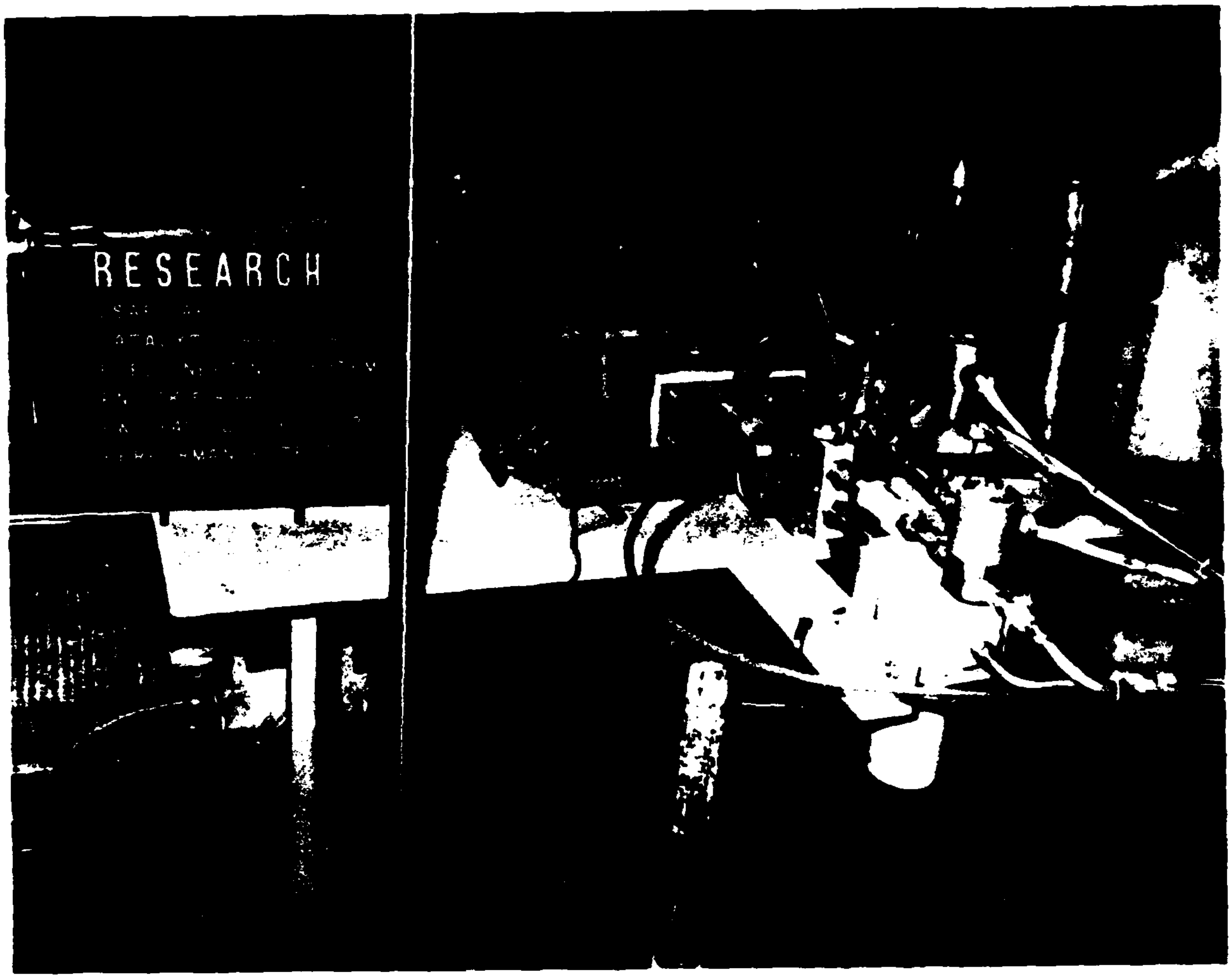


Figure 9. Laboratory Reactor Test Setup

reactor is maintained by a shutoff and flow-control valve in the reactor exhaust line. Inert gas oxygen content was monitored continuously with a Beckman Oxygen Analyzer model F-3. Carbon dioxide concentration was also measured continuously with a Beckman Infrared Analyzer IR-15A. Periodic samples were taken for complete chemical analysis of inert gas composition.

(3) The ram air is derived from the same filtered air source as the bleed air. A throttle valve in the supply line provides flow control capability. An electrical heater upstream of the reactor is used to control ram-air temperature at the desired level (up to 640°F). No provisions were made for control of ram-air pressure.

c. Test Procedure

The test procedure consisted of stabilizing ram- and bleed-air flows, temperatures, and pressures at the level desired for a particular test. Then fuel flow was initiated by opening the fuel shutoff valve. The following parameters were monitored after stabilization:

Bleed-air inlet temperature

Bleed-air flow

Bleed-air outlet temperature

Ram-air inlet temperature

Ram-air flow

Ram-air outlet temperature

Fuel flow

Reactor back pressure

Catalyst bed surface temperature (28 sensors)

Inert gas oxygen content

Inert gas carbon dioxide content

d. Results

(1) Overall Test Program

Forty-one runs were made for a total approximate running time of 80 hr. Additional time was accumulated on the test rig to check out the instrumentation periodically and also to verify operation after alterations or changes made during the test program. A summary of the data is presented in Table III.

TABLE III

LABORATORY REACTOR PERFORMANCE DATA SUMMARY

Run	Flow Confi-guration	Bleed Air		Ram Air				Fuel-Air Ratio	Reactor Pressure, psia	Inert Gas		Ram/Bleed Air Flow Ratio	Catalyst Bed Temp., °F	
		Flow, lb/min	Inlet Temp, °F	Flow, lb/min	Inlet Temp, °F	Outlet Temp, °F	ΔP, in. Hg			O_2 Conc., % vol	CO_2 Conc., % vol		Maximum	Average
101	Counter	0.25	575	5.0	501	501	11.6	---	14.7	21.0	---	20.0	515	---
102	Counter	0.25	537	5.0	512	575	12.2	0.06	14.7	15.1	5.4	20.0	660	595
103	Counter	0.25	580	3.75	519	585	3.65	0.06	14.7	11.8	7.3	15.0	685	618
104	Counter	0.25	535	3.75	508	629	8.8	0.084	14.7	11.6	7.4	15.0	735	670
105	Counter	0.25	508	2.50	503	710	5.5	0.084	14.7	10.2	7.7	10.0	800	740
106	Counter	0.25	535	1.25	510	935	2.1	0.084	14.7	8.0	7.6	5.0	1135	845
201	Counter	0.25	562	2.50	517	750	5.1	0.084	14.7	10.5	7.6	10.0	930	800
202	Counter	0.25	695	1.25	510	1026	2.4	0.092	14.7	8.4	7.7	5.0	1260	1025
203	Counter	0.25	587	1.25	514	1015	2.4	0.112	14.7	8.3	7.5	5.0	1215	1050
204	Counter	0.25	567	1.25	513	998	2.4	0.132	14.7	8.2	7.3	5.0	1180	1010
401	Counter	0.273	452	1.18	528	975	2.3	0.084	14.7	9.1	7.6	4.3	1345	1140
402	Counter	0.276	431	1.16	526	1000	2.3	0.109	14.7	8.2	7.4	4.20	1265	1145
403	Counter	0.276	405	1.18	525	948	2.3	0.109	14.7	8.1	7.3	4.28	1280	1140
404	Counter	0.274	405	1.16	518	984	2.25	0.127	14.7	6.8	4.3	4.23	1280	1130
405	Counter	0.25	471	1.20	507	940	2.15	0.120	29.7	6.2	5.2	4.8	1120	975
406	Counter	0.356	421	2.07	507	855	4.3	0.126	29.7	7.3	6.9	5.81	1070	962
407	Counter	0.351	400	1.64	518	913	3.35	0.128	29.7	7.2	6.7	4.67	1195	1023
501	Counter	0.254	440	1.20	497	893	2.30	0.118	29.7	6.8	6.2	4.72	1155	995
502	Counter	0.263	438	1.08	492	948	2.00	0.114	29.7	7.8	7.0	4.11	1190	1035
504	Parallel	0.24	430	1.16	632	762	1.80	0.125	29.7	7.5	6.7	4.83	1030	670
505	Parallel	0.25	420	1.16	681	873	1.85	0.16	29.7	9.0	7.5	4.64	1130	765
601	Parallel	0.240	454	1.13	685	925	1.85	0.125	31.2	8.4	7.3	4.71	1200	820
602	Parallel	0.324	328	1.15	527	1030	2.40	0.093	14.7	---	---	3.55	1440	1238
603	Parallel	0.264	295	1.02	555	1195	1.10	0.075	14.7	4.6	10.5	3.86	1380	795
604	Parallel	0.267	292	0.98	548	1042	0.95	0.067	14.7	4.5	10.9	3.67	1220	675
605	Parallel	0.270	275	0.90	538	1165	1.15	0.130	14.7	3.7	9.7	3.33	1335	1235
606	Parallel	0.256	259	0.90	536	1130	1.00	0.137	14.7	6.6	7.8	3.52	1345	1140
701	Parallel	0.248	292	0.90	538	1065	1.1	0.141	31.3	6.0	8.3	3.63	1205	1125
702	Parallel	0.200	265	0.91	530	807	1.1	0.175	44.9	0.1	9.0	4.55	845	800
703	Parallel	0.248	318	0.92	560	940	1.1	0.141	14.7	7.3	7.8	3.71	1255	890
704	Parallel	0.236	314	0.85	555	942	1.1	0.148	30.1	5.0	8.7	3.60	1105	1020
705	Parallel	0.208	310	0.85	556	780	1.1	0.168	44.7	1.04	9.8	4.09	875	840
801	Parallel	0.154	310	0.92	558	760	1.11	0.227	46.9	1.3	9.1	5.97	805	780
802	Parallel	0.154	311	0.92	558	775	1.15	0.162	46.5	2.7	9.5	5.97	825	805
803	Parallel	0.154	304	0.94	550	788	1.20	0.129	45.7	4.6	9.2	6.10	850	830
804	Counter	0.168	360	0.80	590	988	1.1	0.208	47.5	4.6	5.4	4.76	955	765
901	Counter	0.336	228	1.31	563	926	1.85	0.178	44.7	5.3	6.3	3.90	1080	900
902	Counter	0.327	262	0.73	575	1166	1.20	0.183	45.7	3.0	6.1	2.23	1340	1000
1001	Parallel	0.236	234	1.14	580	854	1.75	0.148	46.3	6.0	7.4	4.83	1230	680
1002	Parallel	0.219	329	1.10	638	945	1.80	0.114	45.5	0.7	8.5	5.02	1295	770
1003	Parallel	0.229	246	0.92	618	923	1.35	0.153	45.7	2.5	8.0	4.02	1100	735

Initially (runs 101 through 502), the ram-air flow was circulated through the reactor coolant passages in a counterflow-fashion relative to the fuel-bleed air. Later, the test rig was modified to a parallel-flow arrangement, where most of the significant test data was obtained. The counterflow arrangement was retested (runs 804, 901, and 902) to verify the findings obtained previously. The first series of tests represent an attempt at determining the effect of the system parameters on reactor performance as measured by inert product gas-oxygen concentration.

The first tests (runs 101 and 102) were conducted at near stoichiometric fuel-air ratios and relatively large ram-to-bleed-air ratio; reactor temperatures were low, around 700°F, and less than half the bleed-air oxygen was reacted with the fuel. Inert gas oxygen contents of 15.1 and 11.8 percent were measured.

To reduce the oxygen content of the product gases, the ram-air flow was reduced, and also the fuel-air ratio was increased in steps from stoichiometric to nearly twice stoichiometric (runs 103 through 204). As a result, higher reactor temperatures were obtained and inert gas oxygen content was reduced, but remained above 8 percent. These data were verified in runs 401 through 404.

Further runs were made (405 through 502) at a higher reactor pressure to reduce the velocity through the catalyst bed. Generally, slightly lower oxygen concentrations were obtained in the product inert gas, but the oxygen levels obtained (4 to 5 percent) were much higher than desired.

Throughout this test period with the counterflow arrangement, it was noticed that the temperatures at the front end of the reactor were very high with ram-to-bleed-air ratios of about 5. For example, the reactor temperatures measured upstream of the catalyst bed during run 203 were 1180°F. Also indicative of the high reactor-inlet temperatures was the damage sustained by the seals between the reactor and the bleed and ram air ducts. After run 204, shutdown was necessary due to excessive fuel injector temperatures. After run 407, fuel flashing upstream of the catalyst bed was identified. Possibly this phenomenon had occurred previously.

To reduce the reactor temperature upstream of the reactor and thus chill the oxidation reaction, the ram-air circuit was changed to provide parallel flow of ram and fuel-bleed air. Basically, the parallel flow configuration was used for the remainder of the development test program. Only three additional runs were conducted with the counterflow configuration (runs 804, 901, and 902). Again, reaction propagation was noticed upstream of the catalyst bed resulting in shutdown of the test unit after run 804. No fuel flashing problems were noticed with the parallel flow configuration.

Examination of Table III shows generally lower inert gas oxygen concentration with the parallel flow configuration. This may be due to several effects, such as better temperature distribution, higher reactor operating pressures, and generally higher fuel-air ratios. The effect of these parameters is discussed in more detail in the following paragraphs.

It is significant that several runs were made where the oxygen content of the inert gas was lower than 2 percent; however, these low O_2 concentrations were obtained at rich fuel-air ratios, at least twice stoichiometric. Even with the parallel flow configuration attempts made to run at stoichiometric conditions resulted in instability and high reactor inlet temperatures conducive to fuel ignition upstream of the catalyst bed. This fuel ignition problem was not identified as such at the time. Reevaluation of the data in the light of experimental data gathered later, however, indicated that the instability problems were most probably due to fuel ignition upstream of the bed.

Testing of the laboratory unit was discontinued when the low-flow prototype reactor (1 lb/min) and the scale model (6 lb/min) of the high-flow unit were made available for test.

(2) Reactor Performance

(a) Effect of Ram-Air Flow

Reactor temperature profiles for ram-to-bleed-air ratios between 5 and 20 are plotted in Figure 10. Flow configuration is counterflow and bleed-air flow was constant through these runs. As anticipated, the overall reactor temperature is largely controlled by the ram-air flow rate. It should be noticed here that the fuel oxidation reaction proceeds at a much higher rate at higher reactor temperature; about twice as much oxygen was reacted with a 5:1 ram-bleed-air flow ratio than with a 20:1 ratio. Thus, the exothermic heat of reaction at the low ram-air flow is about twice that of the high ram-air flow. This factor contributes significantly to the higher temperature noticed, particularly at the front of the catalyst bed.

As a result of these early tests, the ram-to-bleed-air flow ratio was maintained at about 5:1 for the remainder of the laboratory reactor test program.

(b) Effect of Flow Configuration

As mentioned previously, two ram-air flow patterns (relative to the fuel-bleed air flow) were investigated: counterflow and parallel flow. Figure 11 presents temperature plots along the catalyst bed surface for two pairs of similar test runs. These data are typical of the temperature profiles obtained with parallel and counterflow configurations. As shown, the reactor inlet temperatures are significantly higher in the counterflow case. These high temperatures are conducive to flashing, upstream of the catalyst bed.

(c) Effect of Fuel-Air Ratio

The stoichiometric oxidation of fuel to carbon dioxide and water can be expressed by

$$C_{10}H_{20} + 15\,O_2 + \frac{79}{1.4}N_2 \rightarrow 10\,CO_2 + 10\,H_2O + \frac{79}{1.4}N_2 \qquad (1)$$

RUN	BLEED AIR FLOW, LB/MIN	FUEL/AIR RATIO.	RAM/BLEED AIR RATIO	INERT GAS	
				O_2 CONTENT, % VOL	CO_2 CONTENT, % VOL
102	0.25	0.06	20	15.1	5.4
104	0.25	0.084	15	11.6	7.4
105	0.25	0.084	10	10.2	7.7
106	0.25	0.084	5	8.0	7.6
COUNTERFLOW CONFIGURATION					

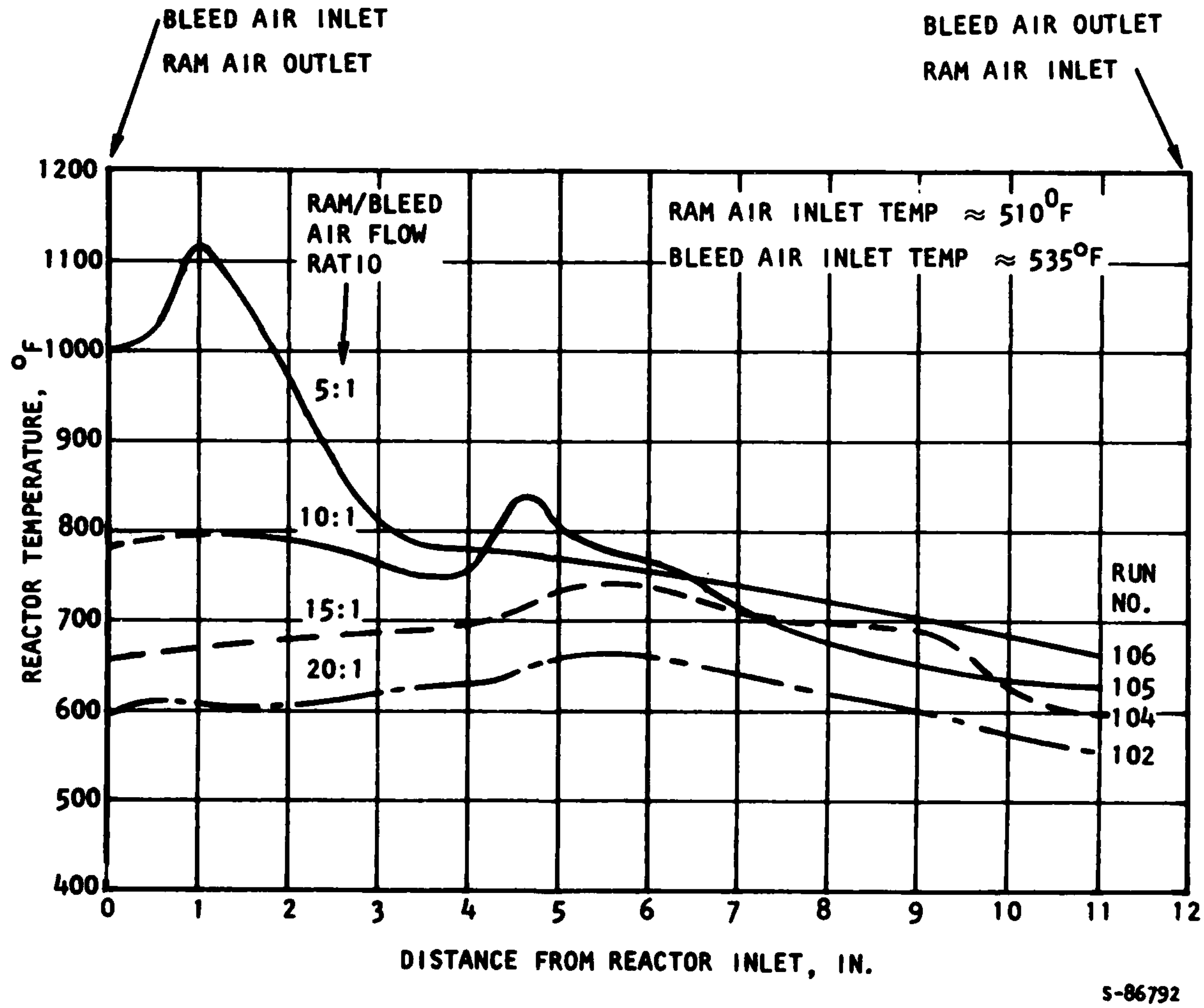


Figure 10. Effect of Ram-Air Flow

RUN	FLOW CONFIGURATION	BLEED AIR		FUEL/AIR RATIO	RAM/BLEED AIR RATIO	RAM AIR INLET TEMP, °F	INERT GAS	
		FLOW, LB/MIN	TEMP, °F				O_2 CONTENT, % VOL	CO_2 CONTENT, % VOL
405	COUNTERFLOW	0.25	471	0.120	4.8	507	6.2	5.2
601	PARALLEL FLOW	0.24	454	0.125	4.71	685	8.4	7.3
REACTOR PRESSURE ≈ 30 PSIA								
801	PARALLEL FLOW	0.154	310	0.227	5.97	588	1.3	9.1
804	COUNTERFLOW	0.168	360	0.208	4.76	590	4.6	5.4
REACTOR PRESSURE ≈ 47 PSIA								

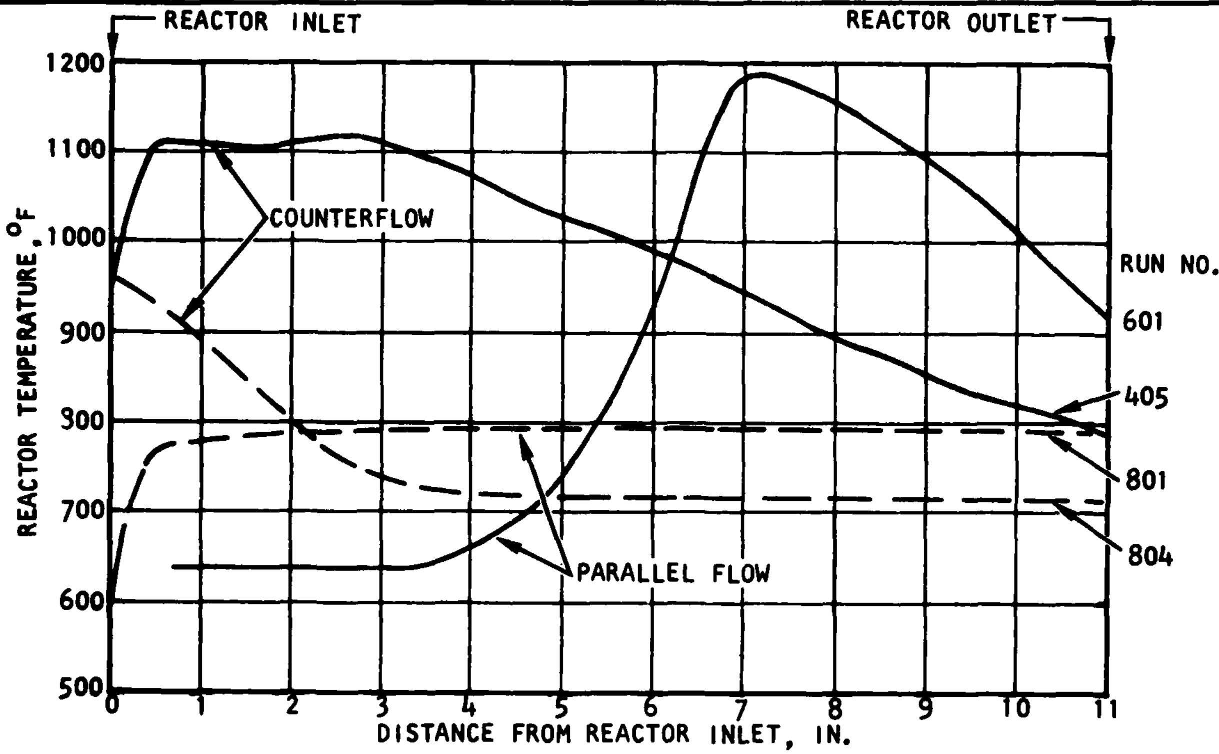


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Figure 11. Effect of Flow Configuration

This reaction represents complete combustion of the fuel. The product gas is clean, with no formation of higher hydrocarbons and tars. This is the reaction sought for the production of inert gas by catalytic air reduction with fuel.

The stoichiometric fuel-air ratio according to reaction (1) above is calculated to be 0.068-lb fuel/lb air. The reaction is exothermic; 18,500 Btu/lb of fuel is released. In terms of the oxygen reacted, the heat released is 5396 Btu/lb O_2.

During conditions when oxidation is incomplete due to inlet gas composition, catalyst effectiveness, and reactor operating conditions, a number of other reactions are possible that result in the formation of carbon monoxide, ethane, methane, and various other hydrocarbons. During the laboratory unit test program, two samples of the reactor exhaust gas were taken for complete chemical analysis (runs 404 and 705). These data are presented in Table IV.

Examination of the data indicates that in both cases the fuel-air ratio is much higher than stoichiometric: 1.86 times stoichiometric for run 404 and 2.47 times stoichiometric for run 705. In both cases, the quantity of carbon monoxide produced is very high by comparison to carbon dioxide. Also, significant quantities of combustible hydrocarbons were produced. This was attributed to the high fuel-air ratios used in these runs.

Throughout the laboratory unit test program, attempts were made to operate the reactor at fuel-air ratios near stoichiometric. Difficulties were encountered due to:

- High reactor inlet temperatures during counterflow operation
- High reactor temperatures exceeding the construction material limitations
- Propagation of the hot reaction zone toward the front of the bed, resulting in instability
- Relatively high concentration of oxygen in the reactor product gas

(d) Effect of Operating Parameters

In general, the effectiveness of a catalytic reactor in promoting a given reaction can be expressed by the following relationship

$$\ln\left(\frac{P_{inlet}}{P_{outlet}}\right) = \frac{A\ P_r K}{M} \qquad (2)$$

TABLE IV

REACTOR EXHAUST GAS COMPOSITION

Run 404	
Flow configuration	Counterflow
Bleed-air flow	0.274 lb/min
Fuel-air ratio	0.127
Ram-bleed-air ratio	4.23
Maximum reactor temperature	1280°F
Average reactor temperature	1130°F
Constituent	**Concentration, % volume**
Oxygen	6.8
Carbon dioxide	4.27
Carbon monoxide	3.0
Methane	0.49
Ethane	0.094
Ethylene	0.937
C3 hydrocarbons	0.175
C4 hydrocarbons	0.150
Higher hydrocarbons (as C5)	0.86
Nitrogen and argon (by difference)	83.22
Run 705	
Flow configuration	Parallel flow
Bleed-air flow	0.208 lb/min
Fuel-air ratio	0.168
Ram-bleed-air ratio	4.09
Maximum reactor temperature	875°F
Average reactor temperature	840°F
Constituent	**Concentration, % volume**
Oxygen	1.04
Carbon dioxide	9.78
Carbon monoxide	7.15
Methane	1.19
Ethane	0.16
Ethylene	1.52
C3 hydrocarbons	0.425
C4 hydrocarbons	0.150
C5 hydrocarbons	0.030
Nitrogen and argon (by difference)	78.55

where P is the partial pressure of the gas (in this case, oxygen) at inlet and outlet of the reactor

A is the catalyst surface area that is fixed for a given bed

P_r is the reactor pressure

K is the reaction rate constant that is a function of temperature

M is the mass flow rate through the unit

As mentioned previously, stable operation at stoichiometric fuel-air ratios could not be achieved with the laboratory unit. Under conditions of high fuel-air ratios, very complex reactions take place within the reactor, as evidenced by the product gas analysis. As a consequence, the effects of reactor parameters such as pressure, space velocity, and temperatures on the oxygen content of the product gases is masked by the effect of the high fuel-air ratio on the nature of the competing reactions, and consequently on the heat generated within the unit.

Figure 12 is a plot of the temperature profiles along the bed for the four best runs, in terms of oxygen content of the inert gas. Pertinent reactor parameters are listed in the figure. Examination of the data shows the following:

- In all cases, reactor pressure is high (about 45 psia). This could be anticipated since the relationship expressed by Equation (2) holds for any reaction or combination of reactions occurring within the reactor.

- Reactor temperature is nearly uniform. This indicates that the reaction occurs in the front portion of the bed. The heat released then is carried downstream through the unit by the product gases and the cooling air. If high reaction rates were prevalent throughout the length of the reactor, a positive temperature gradient would exist as heat would be released as the gases proceed downstream.

- The fuel-air ratio exceeds stoichiometric proportions by a factor of nearly 3, in all cases. As discussed previously, this situation was imposed by the operational peculiarity of the reactor.

- Reactor temperature is between 800° and 850°F throughout. Reactor product gas analysis of run 705 indicates that the reactions taking place within the unit yield a considerable proportion of unburned hydrocarbons. Since the potential exothermic heat of reaction of the oxygen is due to the formation of carbon dioxide and water, any reaction where CO is formed rather than CO_2 will result in lower heat generation. Thus, operation at stoichiometric conditions will result in much higher reactor temperatures.

RUN	BLEED AIR FLOW, LB/MIN	FUEL/AIR RATIO	RAM/BLEED AIR RATIO	INERT GAS	
				O_2 CONTENT, % VOLUME	CO_2 CONTENT, % VOLUME
702	0.200	0.175	4.55	0.1	9.0
705	0.208	0.168	4.09	1.04	9.8
801	0.154	0.227	5.97	1.3	9.1
802	0.154	0.162	5.97	2.7	9.5

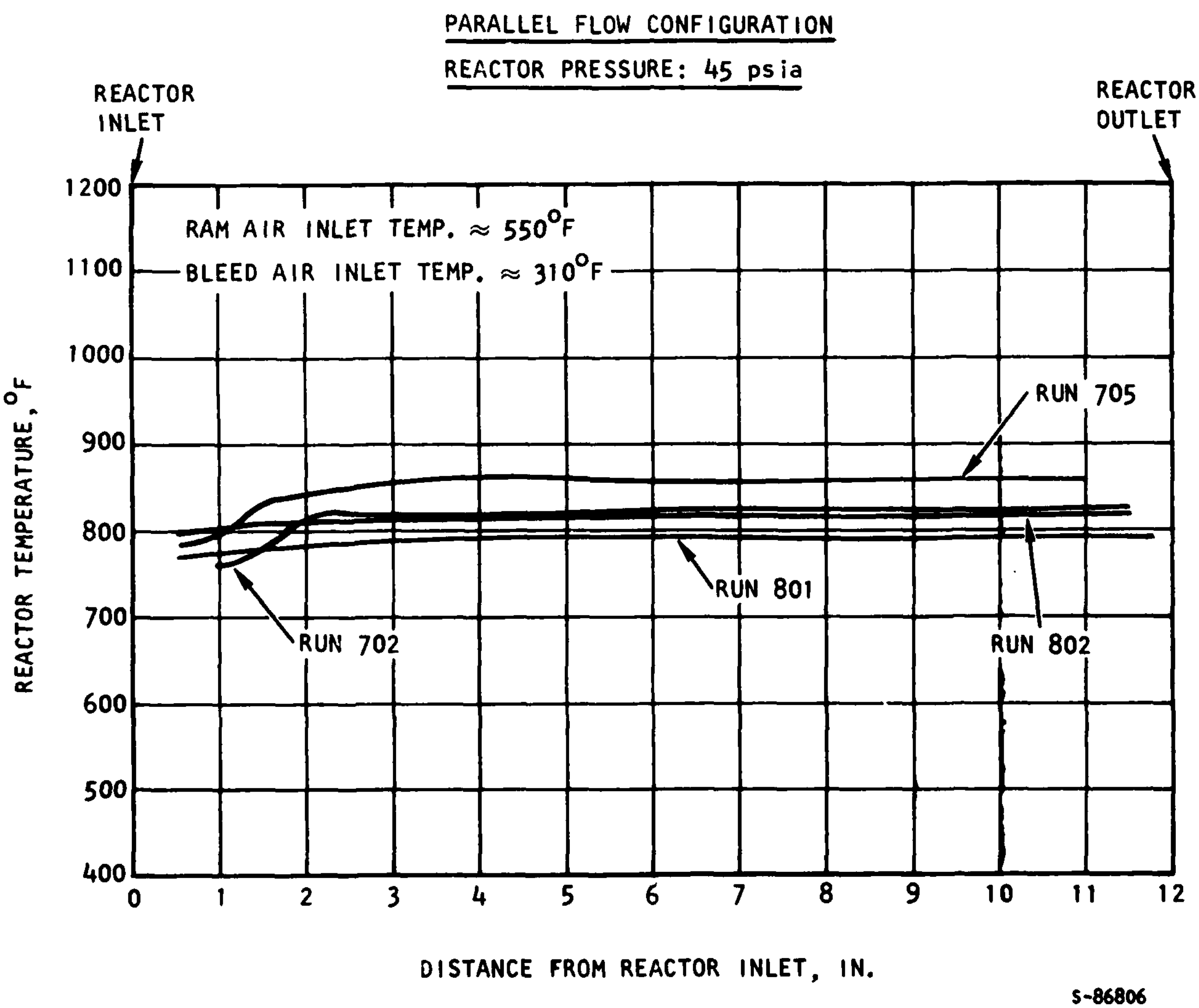


Figure 12. Reactor Temperature Profile at High Reactor Effectiveness

- The bleed-air flow in all cases is significantly lower than the 0.5-lb/min design value. Again, much higher reactor effectiveness can be anticipated according to Equation (2). However, in this case the capability of the reactor to promote reaction (1) was obscured by the limitations imposed by the particular test apparatus on operating at near-stoichiometric conditions. Thus, the effect of channelling due to the presence of the heat transfer surface within the reactor bed could not be determined.

- Ram-bleed-air ratios for the runs shown are between 4 and 6 with ram-air inlet temperatures around 550°F. Although the ram air constitutes the heat sink for the reactor, the complex reactions taking place within the unit under conditions of high fuel-air ratio are believed to be the dominant factors in determining reactor temperature.

e. Conclusions

The laboratory unit test program proved very significant in demonstrating the thermal performance of the unit and the structural capability of the design.

A number of significant conclusions were derived from examination of the test data. These observations were used in the design of the prototype 1-lb/min and 6-lb/min units.

(1) Ignition temperature of reactor. It was found that the oxidation reaction would start at reactor temperatures of approximately 500°F.

(2) Catalyst bed size. Examination of reactor temperature profiles shows that most of the oxidation reaction occurs within a relatively short bed length (2 or 3 in.).

(3) Reaction stability. At the high fuel-air ratios used through most of the test program (2 or 3 times stoichiometric), the reaction was found to be very stable as evidenced by catalyst bed temperatures and oxygen content of the inert gas. At near-stoichiometric fuel-air ratios, instability was encountered.

(4) Reactor pressure. As expected, lower inert gas oxygen concentrations were achieved at higher reactor pressures. The design bleed-air pressure for the flight unit is 45 psia.

(5) Reactor temperature. Reactor effectiveness was found to increase at higher reactor temperatures. This effect is somewhat masked by the high fuel-air ratios used throughout the test program.

(6) Catalyst life. Endurance testing was not performed; however, the reactor operated over a wide range of conditions for about 80 hr with no apparent degradation of the catalyst.

(7) Bed channelling. The effect of channelling due to the presence of finned surfaces within the catalyst bed could not be determined accurately. High effectiveness was obtained at bleed-air flow rates much lower than anticipated (60 to 80 percent of design value), which is indicative of channelling; however, this may be due to the temperature and fuel-air ratio limitations imposed by the requirements for stable operation.

3. SYSTEM DEVELOPMENT

a. Description of Breadboard Reactors

Using the data generated under the laboratory reactor test program, two reactors were designed and fabricated for testing in the breadboard system test setup. The first reactor, designed to generate 1-lb/min inert gas, represents a full-scale version of the unit required to meet the low-flow requirements of the inerting system. The second reactor was a 1/8-scale version of the high-flow unit with inert gas generation capability of 6 lb/min.

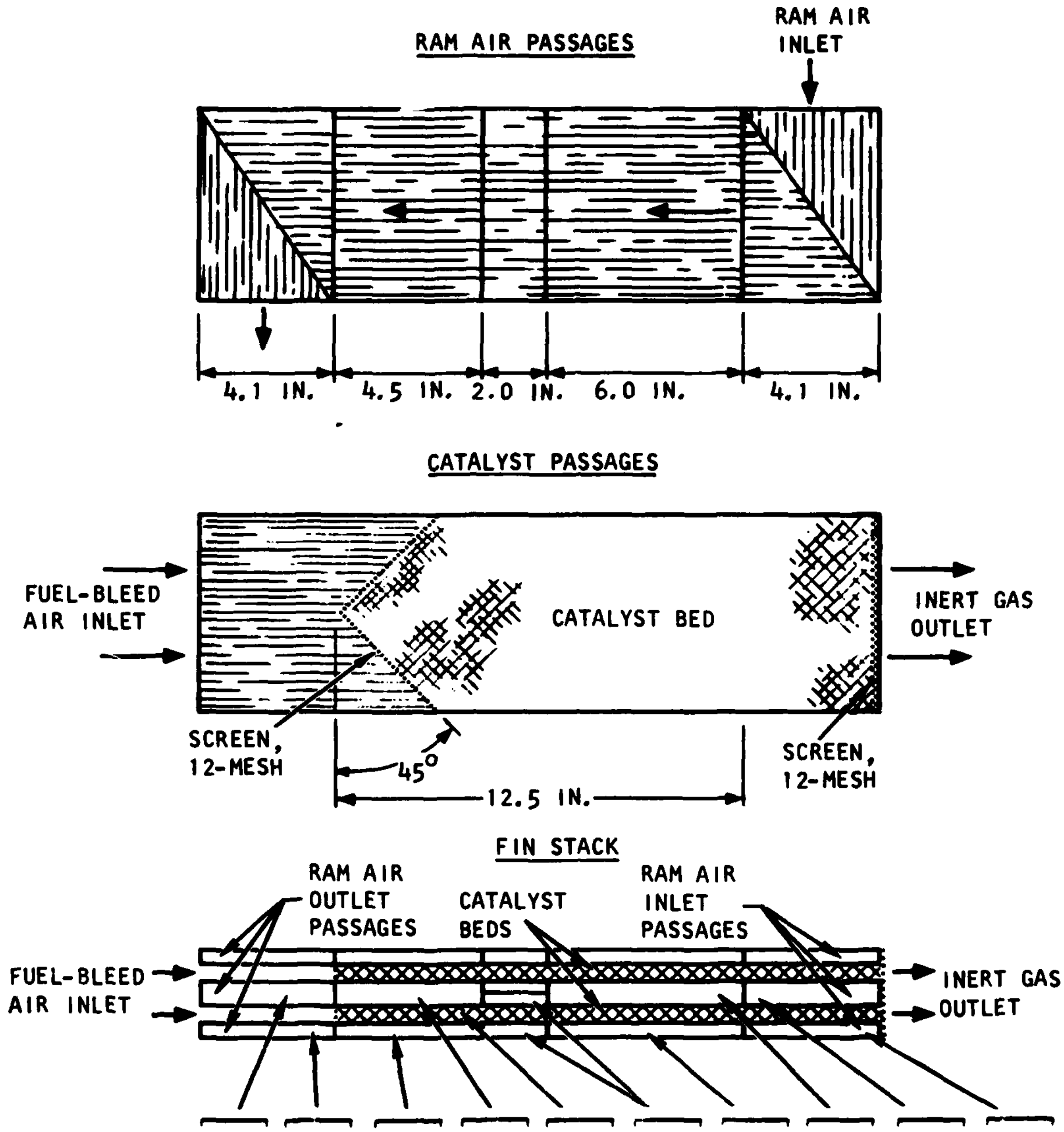
Figure 13 highlights details of the heat transfer surface used on the catalyst and cooling-air sides of the 1-lb/min unit. As shown, the catalyst charge is contained within two finned passages that are 1/4-in. thick; total catalyst volume is 44 cu in. The catalyst charge is contained within the passages by screens. All testing was done with American Cyanamid Code A catalyst.

As shown in Figure 13, the front of the catalyst bed is triangular. This feature was incorporated in the design to minimize the temperature peak in the region of high reaction rates and to reduce thermal stresses in the lateral direction. Thermocouples were incorporated in the design to monitor catalyst bed temperature.

Cooling air passages are provided on both sides of the catalyst layers. The reactor was designed initially as a counterflow unit, although as a result of the laboratory reactor test program, most of the testing was conducted with the cooling ram-air flowing in the same direction as the fuel-bleed-air flow.

The density of the heat transfer surfaces used on the cooling air side varies along the reactor so that much higher thermal capability is provided in the front of the unit where the reaction takes place at a high rate and where the highest thermal gradients are anticipated. Looser fins are used in the back of the unit where the heat transfer rates are lower. This arrangement was designed to minimize thermal stresses along the reactor.

The 6-lb/min reactor is similar in construction to the 1-lb/min unit and consists of 13 catalyst passages separated by 14 cooling-air passages that are identical to the center passage shown in Figure 13. Figure 14 is a photograph of the units taken at the conclusion of the test program. Each catalyst passage has a volume of 22 cu in.



FIN SECTION	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT
FINS PER IN.	10	10	24	24	4	20	12	12	5	5
FIN HEIGHT, IN.	0.312	0.153	0.153	0.312	0.250	0.153	0.153	0.312	0.312	0.153
FIN OFFSET, IN.	-	-	0.111	0.111	-	0.125	-	-	-	-
FIN THICKNESS, IN.	0.004	0.004	0.006	0.006	0.008	0.006	0.004	0.004	0.004	0.004

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Figure 13. Low-Flow Reactor Configuration

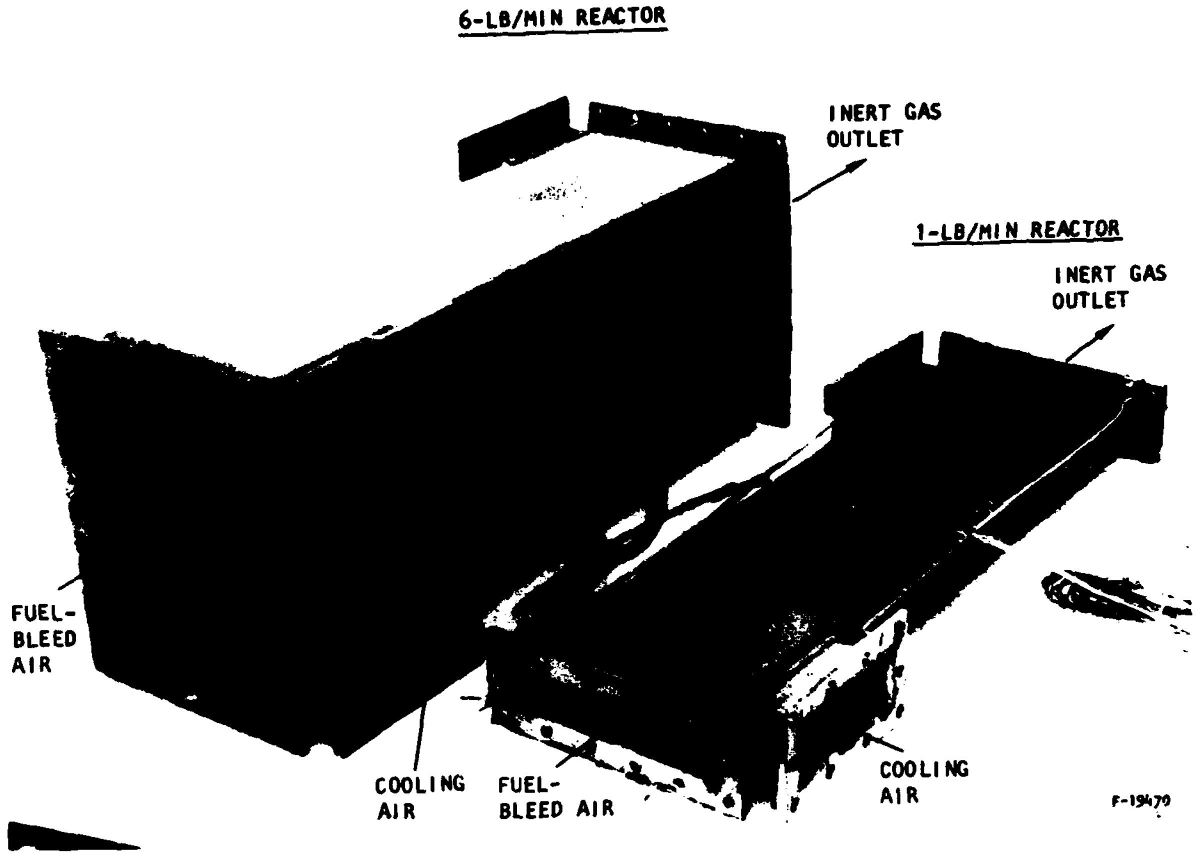


Figure 14. Breadboard Reactors

b. **Fuel Inerting Breadboard System**

The two reactors described above were installed in the breadboard system, shown schematically in Figure 15. Figure 16 is a photograph of the test setup with the 6-lb/min reactor installed. The cooling turbine-fan assembly used in the test setup is from the McDonnell Douglas A-4 program. Major system components, other than the reactors, are shown in Figure 17. Note that in the system configuration shown, ram-air is used for cooling the inert gas in the condenser and also to control reactor temperature. The schematic shows the cooling air flowing in a counterflow direction relative to the bleed-air; most of the testing was done with a parallel-flow arrangement.

c. System Test Program

Exploratory testing of the fuel inerting system was conducted in the high- and low-flow modes with the 6-lb/min and the 1-lb/min reactors. Early in the program, it became apparent that the oxidation reaction could not be contained within the catalyst beds. Fuel combustion upstream and downstream of the catalyst bed occurred frequently over a wide range of operating conditions represented by fuel-air ratio, bleed-air flow, ram-air flow and temperature, and flow configuration (counterflow and parallel flow).

Tests were conducted with the bleed-air temperature at reactor inlet well below the auto-ignition temperature of the particular fuel-air mixtures used. In this manner, the catalyst bed temperature at the front of the parallel-flow reactor could be maintained below the self-sustaining reaction temperature. Under these conditions, the reaction could be started in the back end of the unit; since combustion still occurred upstream of the catalyst bed, it became apparent that the flame front was first developed within the catalyst bed and could rapidly propagate upstream through the bed to the reactor fuel-air feed stream.

Figure 18 is a plot of the temperature along the 1-lb/min reactor immediately after startup. This rapid temperature rise in the front of the bed is typical of the phenomenon occurring in both reactors (low and high flows) at fuel-air ratios near stoichiometric. During operation with lean fuel mixtures and high ram-air cooling flows, the oxidation reaction could be contained within the catalyst bed. A typical reactor temperature profile for these conditions is shown as Figure 19.

After 5-hr operation with the high-flow reactor and under conditions of very inefficient combustion corresponding to only partial reduction of the bleed air, the turbine-fan assembly seized. A tear-down inspection revealed that products of incomplete fuel combustion, in the form of carbon and varnishes, had collected in the seals and bearings. No other apparent damage was found and the unit was cleaned and reassembled. However, it was decided not to install the turbine-fan assembly in the breadboard system until better reactor performance was achieved.

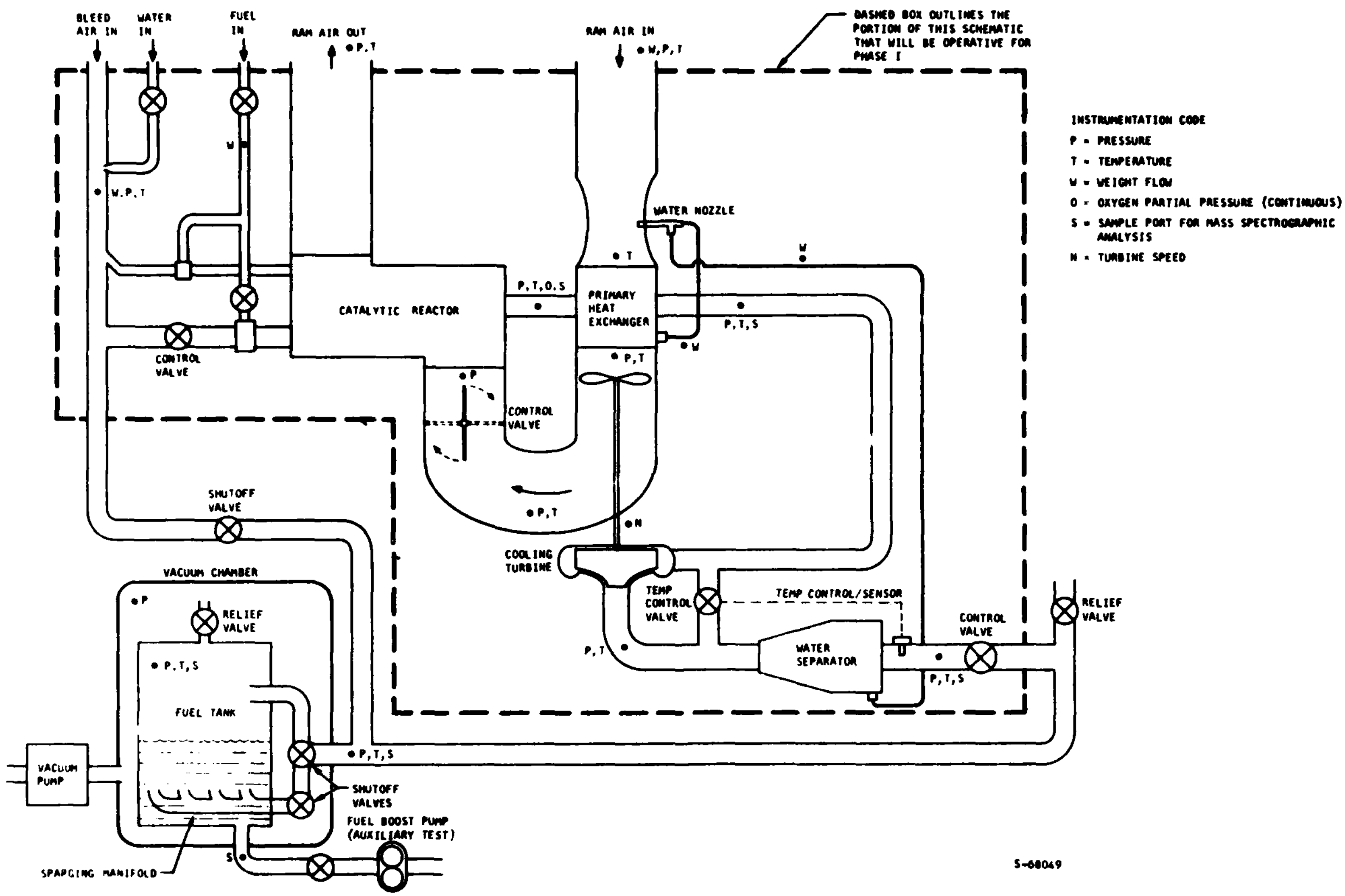


Figure 15. Fuel Inerting Breadboard System

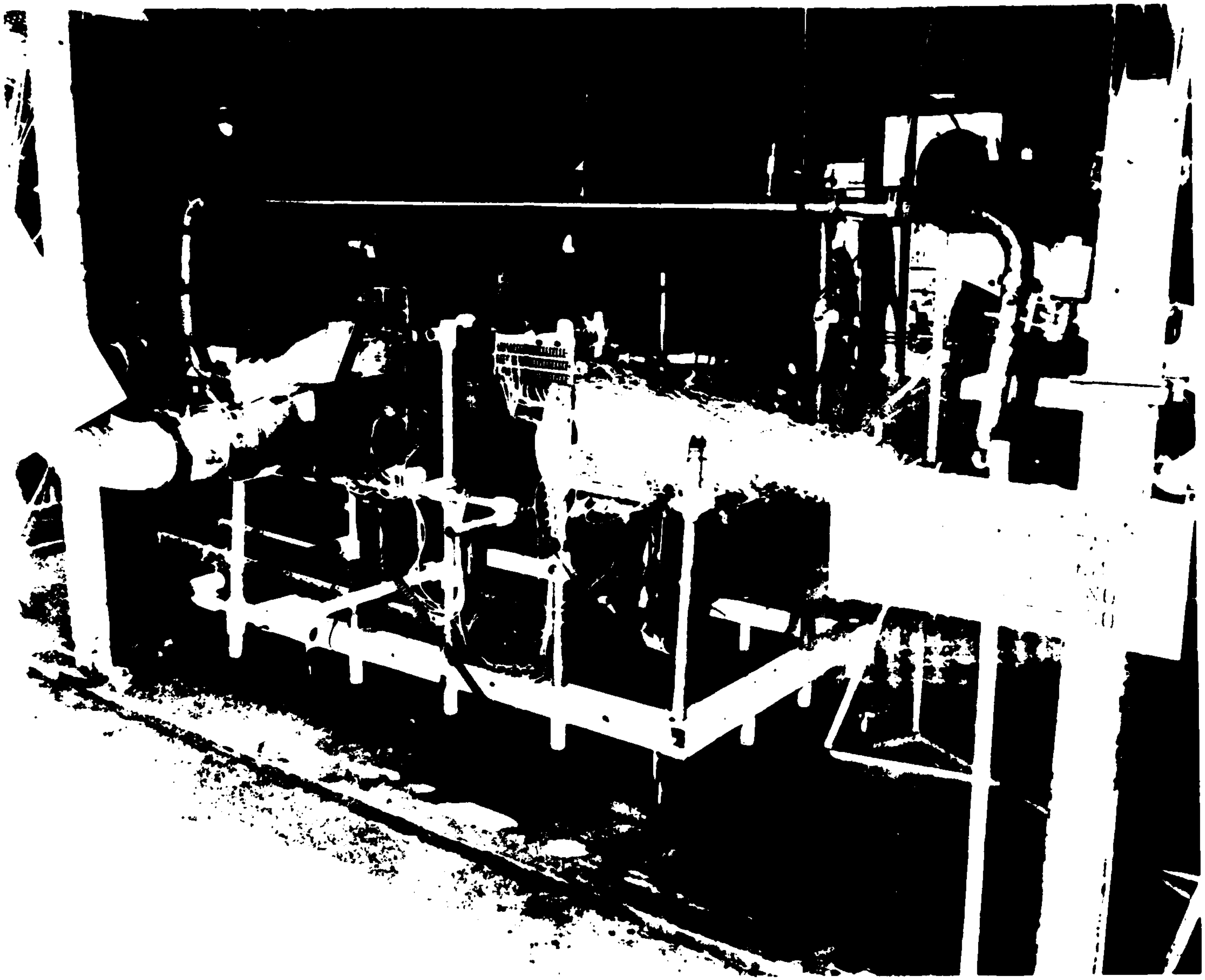


Figure 16. Breadboard System with 6-lb/hr Reactor

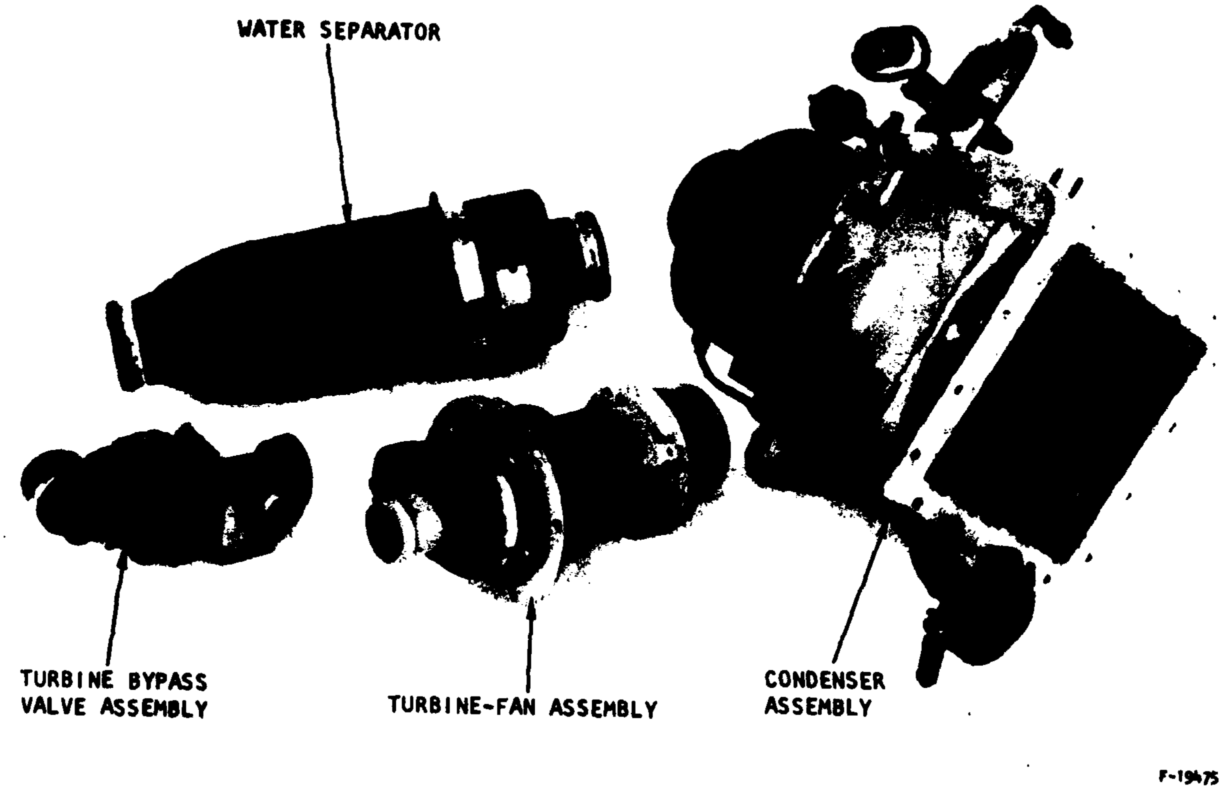


Figure 17. Major Breadboard System Components

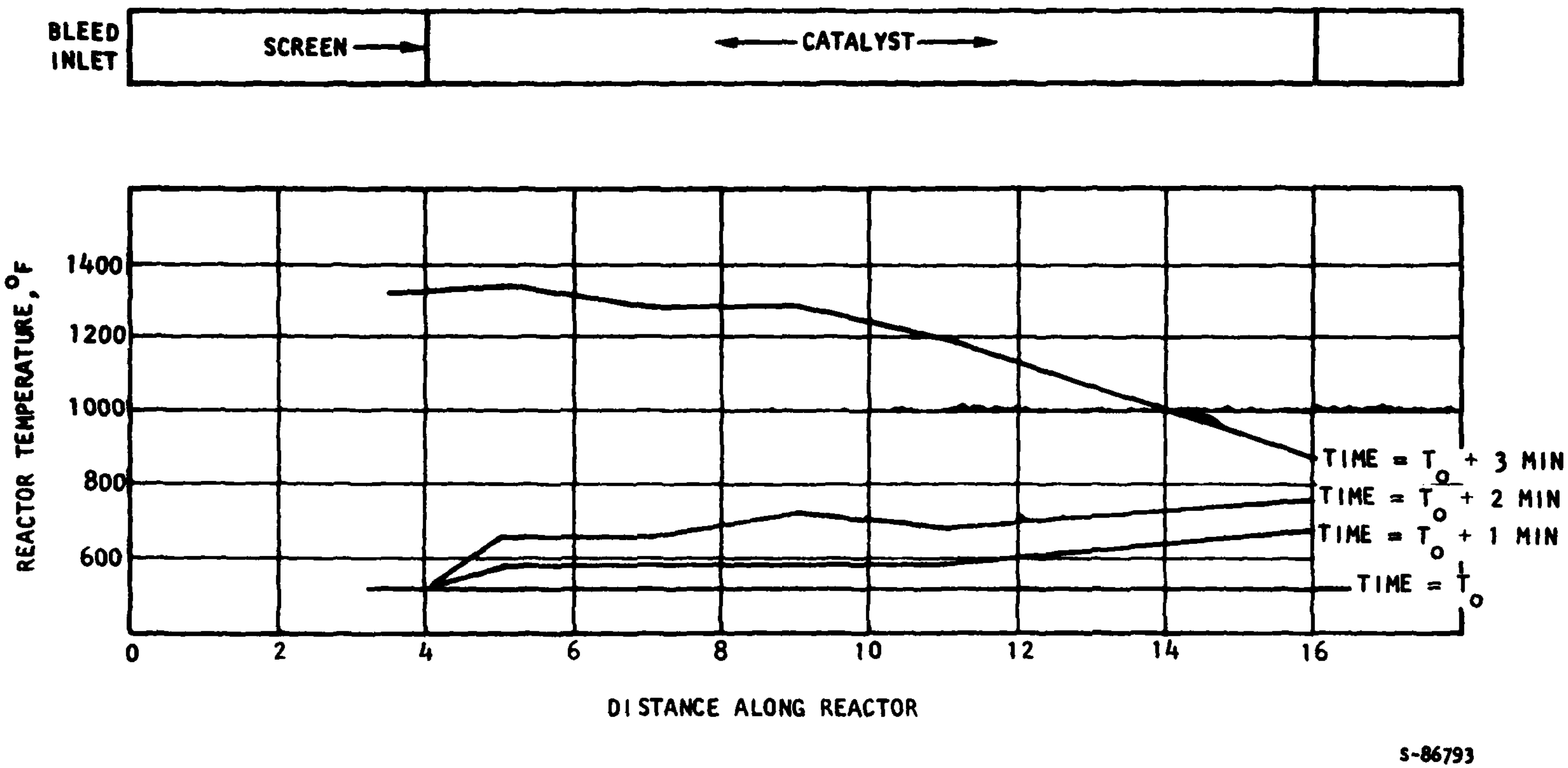


Figure 18. Startup Cycle--Stoichiometric Fuel-Air Ratio

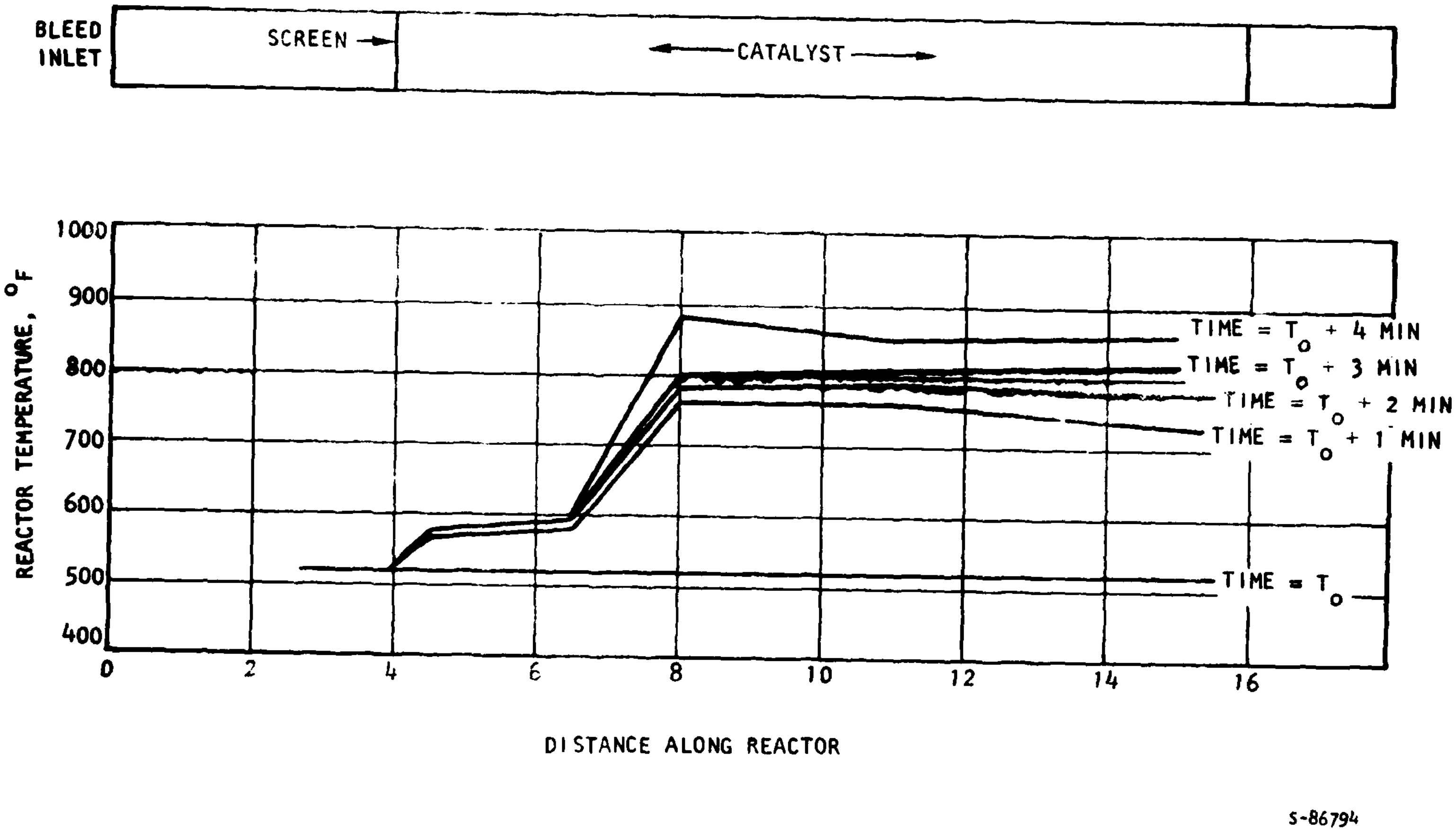


Figure 19. Startup Cycle--Lean Fuel-Air Ratio

Testing of the breadboard system was interrupted and all test activities were concentrated on reactor development in an effort to achieve stable fuel oxidation at low temperature within the catalyst bed. Both the 1-lb/min and the 6-lb/min units were used for this purpose. Two approaches were investigated experimentally:

(1) Recirculation of inert gas around the reactor to effectively reduce the fuel-air ratio upstream of the reactor

(2) Incorporation of a flame arrestor upstream of the catalyst bed

This phase of the development program is described in the following paragraphs.

4. RECIRCULATION SYSTEM DEVELOPMENT

a. Recirculation Loop Description

To resolve flame propagation upstream of the catalyst bed, a system configuration was investigated wherein inert gas from the reactor outlet was mixed with the fuel-bleed-air mixture at the reactor inlet. In this manner, the oxygen concentration of the fuel-air mixture at the reactor inlet was reduced considerably, and below flammability limits. Such a system arrangement is depicted in Figure 20; Figure 21 is a photograph of the modified test setup.

Bleed-air ejectors are used to recirculate the inert gas. Fuel is injected and vaporized in the diluted mixture of bleed and recirculated air upstream of the reactor. Fuel flow is controlled to provide a stoichiometric ratio of fuel-bleed air. This results in a very lean nonflammable mixture at the reactor inlet.

b. Recirculation System Performance

The recirculation system was assembled using the 6-lb/min reactor. A modulating valve in the inert gas return line was used to control the recirculation flow rate during the test. The system was operated over a wide range of fuel-bleed-air ratios; flashing upstream and downstream of the unit occurred until startup procedures were finally developed that resulted in stable operation. The startup sequence consisted of heating the catalyst bed with a fuel-bleed-air mixture only (without recirculation of inert gas). After the bed temperature stabilized without fuel flashing at the inlet, the modulating valve was opened to allow inert gas return to the reactor inlet.

Table V presents typical performance data obtained with the recirculation system at fuel-bleed-air ratios near stoichiometric. Note that although the reactor was designed for 6-lb/min bleed-air flow, good performance was obtained at much higher total flow rates (see runs 1 and 7). In these conditions, the total oxygen reacted is only about two-thirds of design value for this reactor; however, the oxygen concentration of the inlet gas stream is only about half the design value.

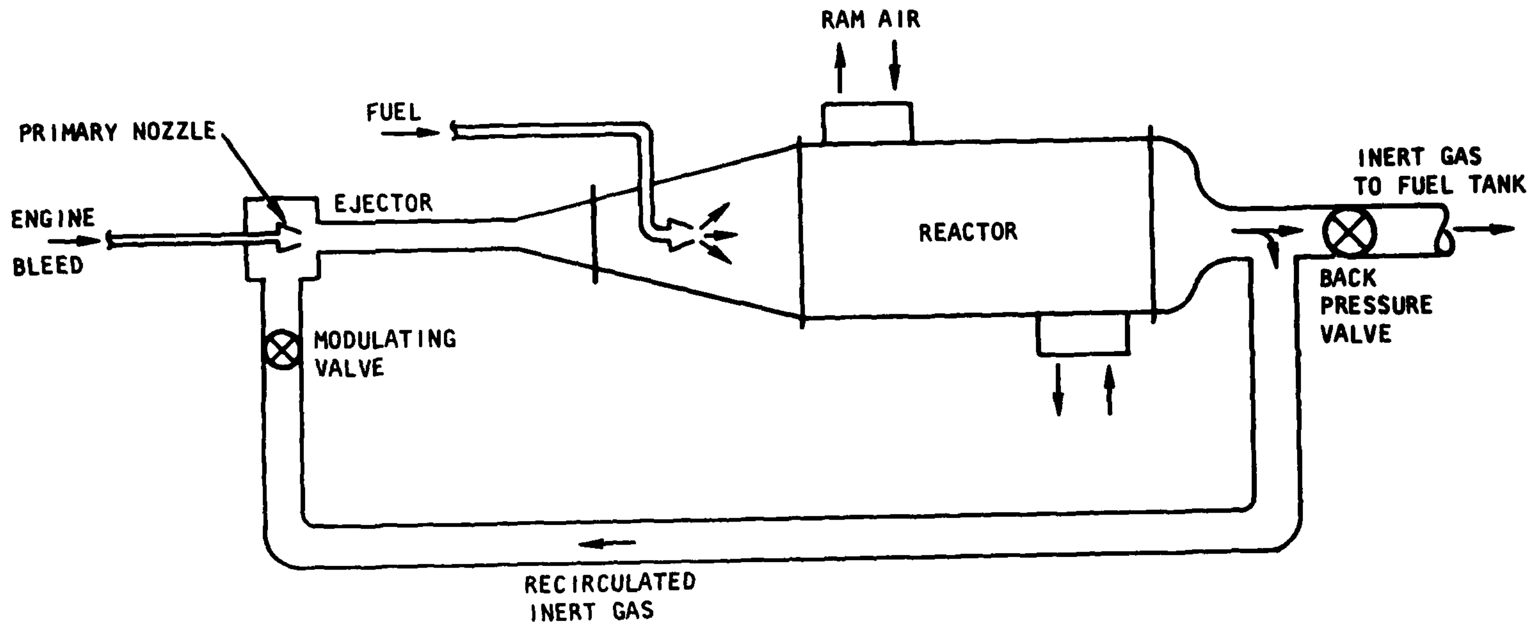


Figure 20. Recirculation System Schematic

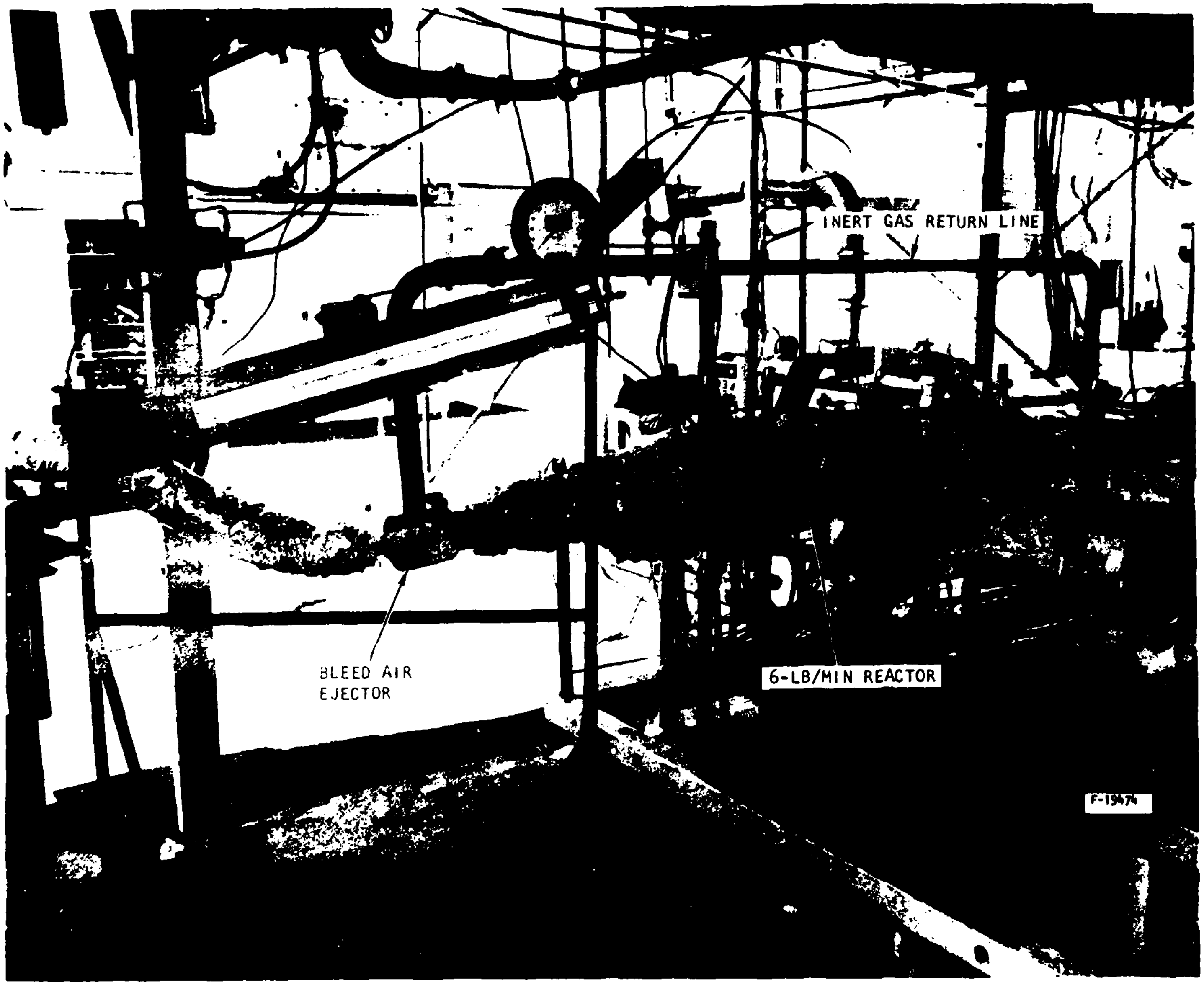


Figure 21. Recirculation Breadboard System

TABLE V

RECIRCULATION REACTOR TYPICAL PERFORMANCE

Run	Flow, lb/min				Recirc-Bleed-Air Ratio	Fuel-Bleed-Air Ratio	Ram-Bleed-Air Ratio	Ram-Total Air Ratio	Temperature, °F		Reactor Inlet		Reactor Exhaust Gas Concentration, % vol		
	Bleed*	Recirc	Ram	Fuel**					Reactor in/out	Ram in/out	Press., psia	O_2 %	O_2	CO_2	CO
1	4.1	5.7	32.0	0.272	1.39	0.066	7.8	3.3	570/990	642/907	62.4	10.3	2.75	10.75	2.5
2	4.0	4.7	28.4	0.272	1.175	0.068	7.1	3.3	540/970	640/895	44.7	11.8	4.20	10.25	2.0
3	4.0	5.2	28.2	0.272	1.3	0.068	7.05	3.1	550/975	644/902	36.8	11.4	4.4	10.1	3.0
4	4.8	6.5	45.5	0.34	1.35	0.070	9.48	4.0	558/1015	626/885	63.9	11.1	4.1	10.5	2.0
5	5.1	5.9	37.3	0.34	1.15	0.067	7.3	3.4	477/1035	630/860	44.7	13.5	7.8	9.1	1.8
6	5.0	6.5	29.0	0.34	1.30	0.068	5.8	2.5	505/1000	621/710	36.8	14.0	9.5	8.2	1.3
7	4.0	4.3	32.0	0.272	1.08	0.068	8.0	3.8	562/970	634/895	65.0	---	1.8	10.1	1.7

* Bleed flow is routed through the ejector primary nozzle.

** Fuel flow was set to obtain a stoichiometric mixture based on the oxygen being supplied by the bleed air only.

Figure 22 is a plot of oxygen concentration in the inert gas as a function of the recirculated-to-bleed-air flow ratio. The data are presented for stoichiometric fuel-bleed-air ratio. During these tests, the ram and bleed air temperatures were maintained between 500° and 600°F. The plots of Figure 22 confirm the data listed in Table V. Examination of the data shows the following:

(1) Effect of reactor pressure (see runs 4 and 5 by comparison to run 6). Lower reactor outlet oxygen contents were obtained at higher reactor pressures. This confirms the findings of the laboratory reactor test program.

(2) Effect of process flow rate (see runs 1, 2, and 3 by comparison to runs 4, 5, and 6, respectively). Lower total flow rates correspond to lower space velocity over the catalyst bed and higher oxygen reduction rates. The lowest oxygen concentration was obtained at a total 8.3-lb/min flow rate.

A sample of the reactor outlet gas was taken for detailed chemical analysis. Table VI lists the constituents of the inert gas.

The data show that although oxygen reduction was fairly complete, significant quantities of carbon monoxide and hydrocarbons were produced. Tars and heavy condensible hydrocarbons formed in the reactor are entrained to the condenser with the inert gas. These products are removed from the unit with the condensate and do not accumulate on the extended heat transfer surfaces of the condenser.

Further exploratory testing of the 6-lb/min reactor in the recirculation loop revealed that fuel-bleed-air ratio lower than stoichiometric resulted in higher inert gas oxygen content. Conversely, oxygen contents below 2 percent were obtained consistently at richer fuel-air mixtures.

Throughout the test program, it was found that the performance of the reactor in the recirculation loop was very sensitive to operating parameters. To obtain low oxygen concentration at reactor inlet, high reactor performance is necessary. A small increase in the oxygen concentration at reactor outlet will result in higher oxygen concentration at inlet. Under these conditions, the fuel-air mixture can reach flammable proportions and flashing can occur.

Experience gained with the operation of the system over a wide range of conditions indicates that stable operation can be maintained by careful control of the startup sequence, the fuel and air flow rates, and temperatures.

c. Conclusions

The development program conducted on the 6-lb/min reactor in the recirculation loop has demonstrated the feasibility of this approach to prevent uncontrolled fuel burning upstream of the reactor. However, this technique has developmental and inherent disadvantages in comparison with the simple flame arrestor concept.

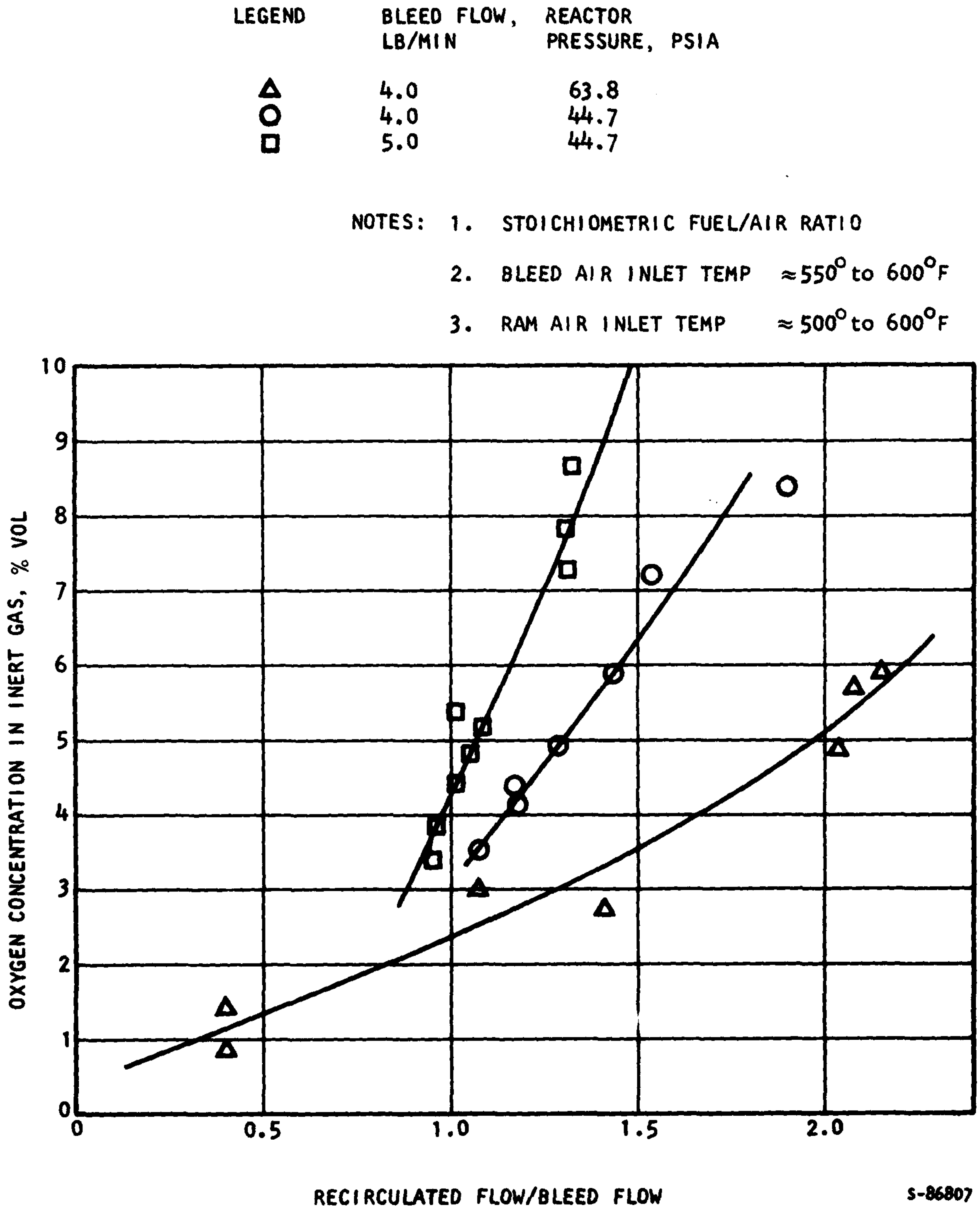


Figure 22. Performance of Breadboard Recirculation System

TABLE VI

RECIRCULATION LOOP INERT GAS COMPOSITION

Constituent	Mole, %
Water	1.125
Nitrogen	83.871
Carbon monoxide	1.671
Oxygen	1.803
Argon	0.988
Carbon dioxide	10.124
Total hydrocarbons	0.418
Tars weight, 14.0 mg	

The following are major disadvantages of the recirculation system:

(1) Sensitivity of the system in terms of system parameters and equipment.

(2) Requirement for carefully controlled startup procedures.

(3) High bleed-air pressure and high bleed-air ejector efficiency is necessary to assure adequate recirculation flow.

(4) Size and weight of the recirculation duct.

(5) High ram-to-bleed-air ratios necessary for reactor temperature control.

In view of these disadvantages and the successful development of an effective flame arrestor (see later discussion), testing of the recirculation concept was terminated. This technique is not recommended.

5. FLAME ARRESTOR DEVELOPMENT

Problems involving combustion downstream of the catalyst bed were resolved by: (1) replacing the catalyst with inert pellets in the portion of the bed adjacent to the ram-air outlet manifold (see Figure 13), and (2) increasing the ram-bleed-air ratio.

The first step eliminates the possibility of high reaction rates in the last 4 in. of the reactor, and the second assures adequate cooling capacity to quench the process gases.

To prevent uncontrolled combustion upstream of the bed, a number of approaches were investigated. Some of the approaches involved wide variations in operating parameters such as: (1) reduced bleed-air flow (0.5 lb/hr), (2) very high ram-bleed-air ratios (as high as 25:1), and (3) low-temperature ram air and/or bleed air. Since stable operation at near-stoichiometric fuel-air ratio would not be achieved, it becomes apparent that the problem could be resolved only by incorporation of a flame arrestor upstream of the bed.

A number of flame arrestors were built and evaluated on the 1-lb/min and the 6-lb/min units (see Figure 23). The first evaluated configurations consisted of stacks of screens installed in the fuel-bleed-air inlet manifold. This approach was not effective in controlling the flame front. Temperature profiles similar to that shown in Figure 18 were obtained. As a result, the screen temperature was too high and flashing occurred repeatedly upstream of the screens.

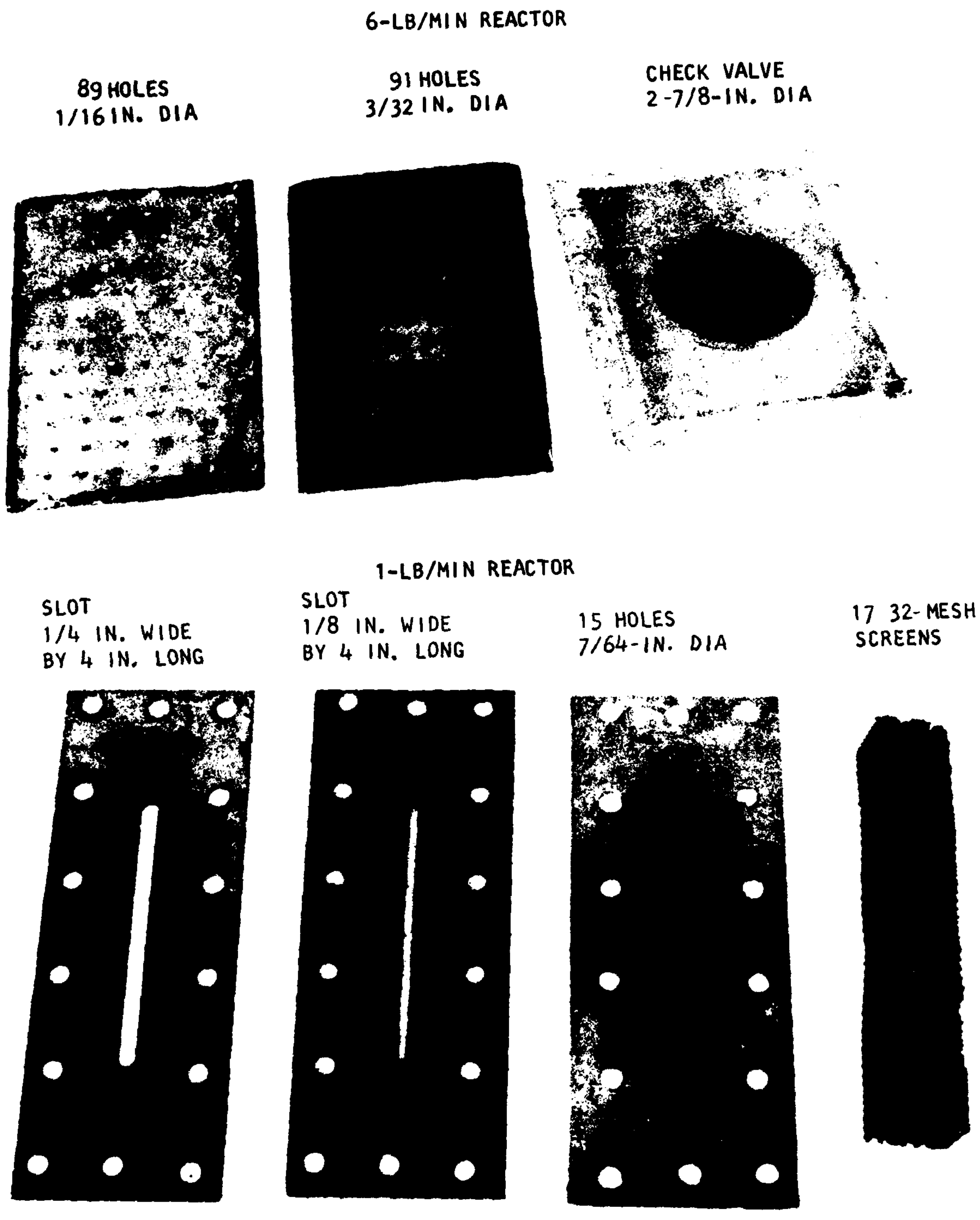


Figure 23. Experimental Flame Arrestors

Other flame arrestor configurations consisted of orifice plates located upstream of the reactor and intended to increase the velocity of the fuel-air mixture above the flame velocity. A series of such orifice plates were tested that provided velocities as high as 100 ft/sec. None of these configurations proved successful. Flame propagation upstream of the orifice plates was attributed to the fact that the flame front could reach upstream to the plate, which resulted in overheating and finally, flashing, upstream of the plate.

As a result of these tests, during which very high reactor temperatures were measured (as high as 1900°F), the 1-lb/min reactor was severely damaged. The heat exchanger (stainless steel) matrix was burned at the inlet, indicative of sustained temperatures of at least 3000°F.

At the conclusion of this test program, it became apparent that the flame arrestor itself had to be cooled. The existing units could not be modified to incorporate such a design. Accordingly, a new 1-lb/min unit (identified as the prototype module) was designed incorporating a cooled flame arrestor immediately upstream of the catalyst bed. This reactor was successfully tested over a wide range of parameters at fuel-air ratios near stoichiometric. Flashing upstream of the flame arrestor never occurred. A detailed description of this prototype module and of the test program conducted are presented in the following subsection.

6. PROTOTYPE MODULE DEVELOPMENT

a. Prototype Module Description

Figure 24 is a photograph of the prototype module taken at the conclusion of the test program. The cooling air passages are identical to those of the previous unit; only the catalyst passages are different. A flame arrestor is incorporated upstream of the catalyst bed. The flame arrestor is 2-in. long and features 106 small, longitudinal passages through which the fuel-air mixture passes before entering the catalyst bed. The cross section of each passage is 0.032 by 0.032 in. The velocity through these small holes is estimated at about 100 ft/sec for a flow of 1-lb/min. Cooling of the arrestor is assured by the ram-air flow in passages on each side of the arrestor. The ram air is circulated in a fashion to assure that the temperature of the arrestor is maintained near that of the ram air at inlet.

The catalyst charge extends from the flame arrestor to the ram-air outlet passages (see Figure 25). In this manner, flame propagation downstream of the reactor is prevented, as shown in previous tests. As a result, the volume available for catalyst loading is reduced to 33.4 cu in.

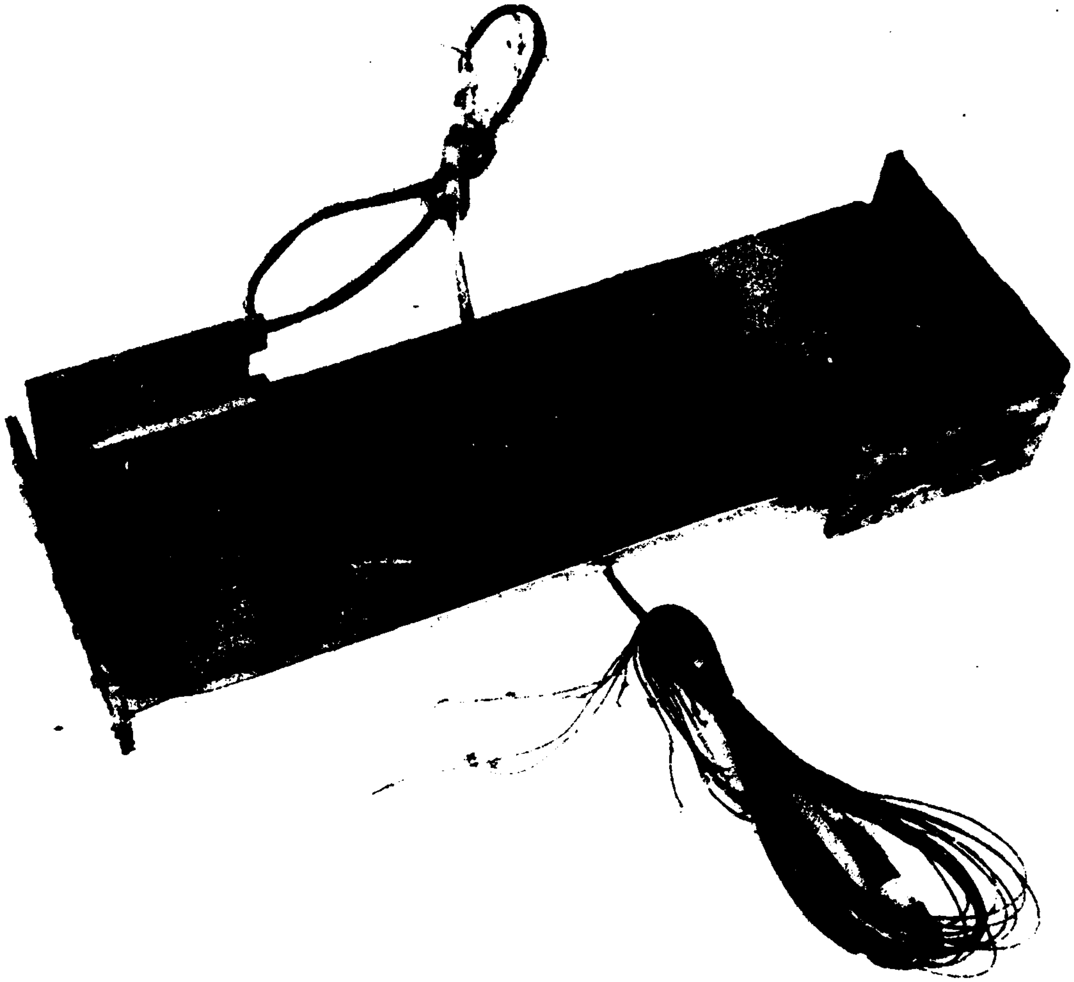
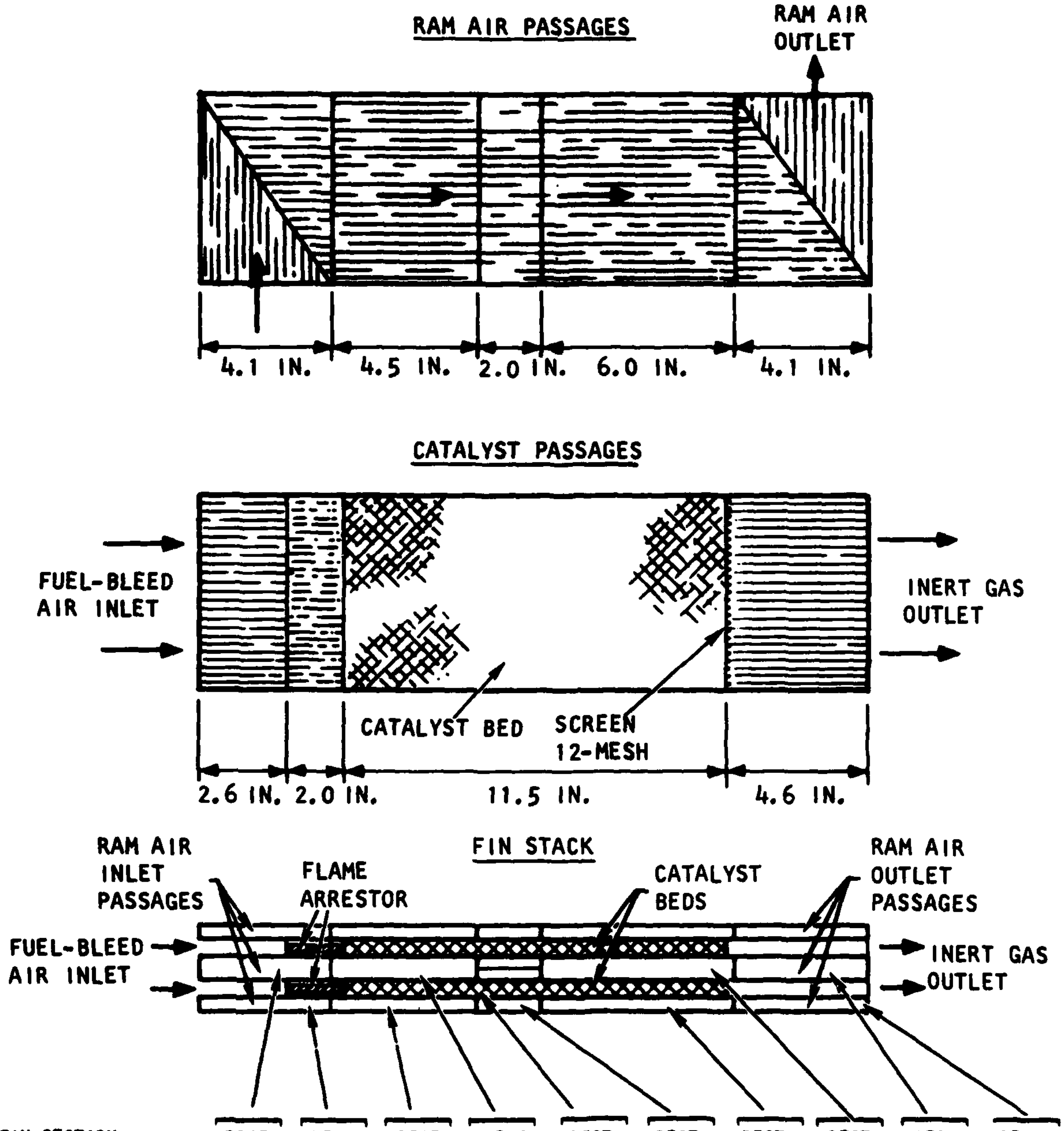


Figure 24. Prototype Module



FIN SECTION	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT	RECT
FINS PER IN.	10	10	24	24	4	20	12	12	5	5
FIN HEIGHT, IN.	0.312	0.153	0.153	0.312	0.250	0.153	0.153	0.312	0.312	0.153
FIN OFFSET, IN.	-	-	0.111	0.111	-	0.125	-	-	-	-
FIN THICKNESS, IN.	0.004	0.004	0.006	0.006	0.008	0.006	0.004	0.004	0.004	0.004

Figure 25. Prototype Module Configuration

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b. Test Objectives

The major objectives of the test program for 1-lb/min prototype module were to:

(1) Verify the effectiveness of the flame arrestor upstream of the catalyst bed.

(2) Determine the effects of operating parameters--fuel-air ratio, bleed-air flow rate, ram-air flow rate, and reactor temperature--on reactor effectiveness in oxidizing the fuel to CO_2 and water. This could not be done accurately with the previous unit because of operational limitations imposed by the combustion problems encountered during the test program.

(3) Determine the composition of the reactor products in terms of heavy hydrocarbons, tars, and also corrosive contaminants such as SO_2.

(4) Generate thermal data for the detail design of a flight prototype reactor and for overall system design.

c. Baseline Test Conditions

The baseline operating conditions of the test rig were derived from a typical bomber fuel tank inerting system requirements in the low-flow mode. The following parameter values formed the basis for generation of parametric performance data:

Flow configuration	Ram-air flow parallel to the fuel-bleed-air flow
Bleed-air flow	1.0 lb/min
Fuel-air ratio	0.068 (stoichiometric)
Ram-air flow	Variable
Reactor temperature	Variable; 1300°F max. peak
Bleed-air inlet temperature	450°F
Reactor pressure	45 psia
Ram-air inlet temperature	450°F

All testing was done at a 45-psia reactor pressure and a 450°F bleed-air inlet temperature. The ram-air flow was a variable test parameter. While it is desirable to minimize the ram-air flow to reduce system penalties and to achieve high reaction rates in a low-weight reactor, limitations are imposed on maximum reactor temperatures by material selection and thermal stress considerations. For these reasons, a reactor temperature of 1300°F was established as the maximum acceptable to prevent structural damage to the test unit.

d. Performance Data Summary

Table VII gives the test performance of the reactor over the entire range of conditions investigated. A cursory examination of the inert gas oxygen concentration is indicative of the significant performance improvement achieved by comparison to test data presented earlier (see Tables III and V). Oxygen concentrations below 2 percent were achieved under most operating conditions of the prototype module. In prior tests, with the laboratory reactor and with the 6-lb/min unit, oxygen concentrations below 4 percent were seldom achieved. Correlation of the data of Table VII with respect to operating parameters and their impact on the design of the inerting system are discussed in the following paragraphs.

e. Flame Arrestor Effectiveness

The flame arrestor proved eminently successful through 60 hours of testing over a wide range of conditions:

Fuel-air ratios	0.9 to 1.4 times stoichiometric
Ram-air flow rates	6 to 19 lb/min
Reactor temperatures	up to 1300°F
Bleed-air flows	0.7 to 2.3 lb/min

The oxidation reaction was contained downstream of the arrestor and combustion of the fuel-air mixture in the inlet stream never occurred.

The ram air (at 450°F) was very effective in maintaining a cool flame arrestor. Typical reactor temperature profiles, measured along the centerline of the unit, are presented in Figure 26. The plots were prepared for a bleed flow of 1 lb/hr and stoichiometric fuel-air ratios. The two temperature levels were obtained by adjusting the cooling ram-air flow (450°F inlet). These temperature plots correspond to tests 16 and 27 of Table VII.

TABLE VII

PROTOTYPE MODULE TEST PERFORMANCE SUMMARY

Run	Bleed Air		Ram Air		Fuel-Air Ratio	Ram-Bleed Air Ratio	Temperature, °F		Inert Gas Composition, % Vol		
	Flow, lb/min	Inlet Temp., °F	Flow, lb/min	Inlet Temp., °F			Max. Reactor	Ram Air Outlet	O_2	CO_2	CO
1	1.0	405	10.0	410	0.068	10.0	1020	777	3.6	10.7	0.5
2	1.0	420	10.0	410	0.068	10.0	1060	790	2.5	11.1	0.3
3	1.0	405	10.0	425	0.068	10.0	1020	805	3.1	10.9	0.3
4	1.0	400	9.7	440	0.068	10.0	1050	815	3.1	10.9	0.3
5	1.0	405	9.9	450	0.068	10.0	990	830	2.8	11.1	0.3
6	1.0	415	10.0	455	0.068	10.0	990	835	2.5	11.2	0.3
7	1.0	435	10.0	455	0.068	10.0	1020	835	2.4	11.2	0.4
8	1.0	455	10.0	455	0.068	10.0	1020	840	2.5	11.2	0.5
9	1.0	465	10.0	455	0.068	10.0	1000	840	2.3	11.2	0.5
10	1.0	470	10.0	455	0.068	10.0	1000	840	2.3	11.2	0.5
11	1.0	450	10.0	450	0.059	10.0	920	770	6.0	10.0	0.5
12	1.0	440	10.1	445	0.080	10.1	1115	815	0.6	10.9	6.8
13	1.0	450	10.0	455	0.096	10.0	1020	795	1.5	8.8	9.6
14	1.0	455	8.0	455	0.068	8.0	1170	915	1.0	11.4	1.6
15	1.0	450	6.2	460	0.068	6.2	1260	1017	0.9	11.6	1.1
16	1.0	440	12.0	455	0.068	12.0	1075	785	1.8	11.3	0.9
17	1.0	450	15.0	460	0.068	15.0	1025	730	1.9	11.2	1.1
18	1.0	450	10.0	455	0.068	10.0	1060	845	1.4	11.7	0.3
19	1.0	450	8.0	450	0.068	8.0	1115	920	1.3	11.8	0.3
20	1.0	445	9.9	450	0.059	9.9	980	795	4.2	10.8	0.3
21	1.15	450	10.0	455	0.068	8.7	1120	890	1.8	11.5	0.3
22	1.3	450	10.2	450	0.068	7.8	1135	935	1.4	11.6	0.4
23	0.85	450	10.0	660	0.068	11.8	1030	785	1.5	11.2	0.5
24	0.7	445	9.8	595	0.068	14.0	945	730	2.6	11.1	0.5
25	1.0	455	10.0	455	0.068	10.0	1120	825	1.6	11.9	0.4
26	1.0	455	8.2	445	0.068	8.2	1270	900	0.7	11.8	0.8
27	1.0	450	7.8	450	0.068	7.8	1300	925	0.7	11.6	1.4
28	1.0	455	10.0	455	0.068	10.0	1215	840	0.8	11.6	0.9
29	1.0	450	10.0	450	0.059	10.0	1085	765	4.9	10.4	0.4
30	1.0	450	8.0	450	0.068	8.0	1275	910	1.2	11.7	0.5
31	1.3	450	10.0	450	0.068	7.7	1300	940	0.8	11.8	0.8
32	1.5	455	12.2	455	0.068	8.1	1295	915	1.1	11.7	1.0
33	1.8	450	14.8	455	0.068	8.2	1300	910	1.55	11.5	1.0
34	2.0	450	15.9	455	0.068	8.0	1295	925	1.95	11.3	1.9
35	2.3	450	18.7	450	0.068	8.1	1300	910	2.1	11.2	2.1
36	0.99	450	5.45	455	0.068	5.5	1290	1018	2.9	11.5	0.7
37	1.0	450	7.0	455	0.068	7.0	1300	952	2.3	11.5	0.3
38	1.0	460	5.7	455	0.068	5.7	1295	1028	1.6	11.7	0.6

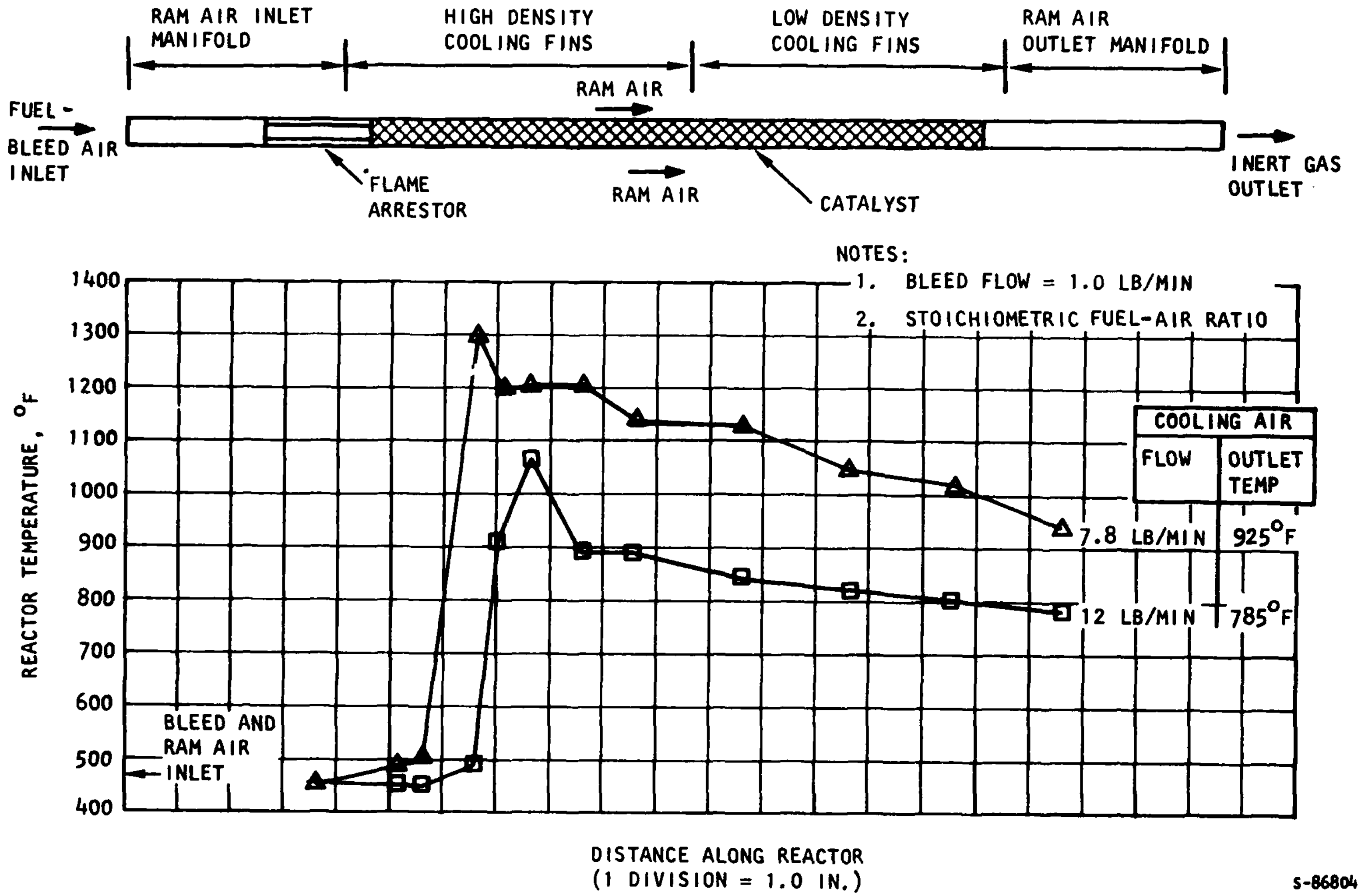

Figure 26. *Effect of Ram-Air Flow on Reactor Temperature Profile*

The effectiveness of the ram-air passages in maintaining a low flame arrestor temperature is illustrated. The metal temperature measured at about midpoint along the flow direction of the flame arrestor is maintained at 450°F in both cases. A survey of all the data shown in Table VII indicates that the flame arrestor temperature never exceeds the 450°F level at midpoint. Also typical of all test runs is the fact that the catalyst temperature immediately downstream of the flame arrestor is always relatively cool, about 600°F max. Consequently, little heat is carried upstream and low arrestor temperature is the result.

f. Effect of Reactor Temperature

The plot of Figure 26 shows a very sharp rise in reactor temperature, starting about 1 in. downstream of the flame arrestor and occurring over a catalyst bed length of 1 to 2 in. This rise is the result of very high rate of heat generation within the catalyst bed. It is believed that the largest portion of the bleed-air oxygen is reacted in that region. The actual oxidation reactions taking place in this particular high activity region of the catalyst bed are not known. However, equilibrium considerations indicate that a number of competing reactions could occur, resulting in the formation of many products; the remainder of the catalyst bed is necessary to achieve complete reaction to CO_2 and H_2O. Experimental data discussed later support this fact.

The reactor temperature is dominated by the ram-air flow. The inert gas composition corresponding to the 1300°F- and 1050°F-temperature reactor profiles of Figure 26 is given in Table VIII.

TABLE VIII

EFFECT OF GAS TEMPERATURE ON INERT GAS COMPOSITION

Constituent	Concentration in Inert Gas, % by volume	
	1300°F Temp Reactor	1050°F Temp Reactor
Oxygen	0.7	1.8
Carbon dioxide	11.6	11.3
Carbon monoxide	1.4	0.9

The exothermic heat of reaction will be about the same in both cases, so the reactor temperature differences are due primarily to the ram-air flow rate. As noted in Figure 26, the reactor immediately downstream of the catalyst bed assumes a temperature very near that of the ram air, even though relatively low-density heat transfer fins are used in the downstream

half of the ram-air passages (see Figure 25). It can be concluded that the heat transfer surfaces on the cooling air side are very effective, and that the thermocouples installed on the plate between the catalyst bed and the ram air passage provide a good measurement of catalyst bed temperatures.

The plots of Figure 26 are typical of those obtained throughout the test program. To prevent damage due to excessive thermal stresses, a 1300°F peak reactor temperature was established as maximum for normal operation. Temperature profiles were monitored throughout the test program as a means of quickly assessing overall reactor operation.

Figure 27 shows the maximum or peak reactor temperature as a function of ram-air flow. The data are presented for a 1-lb/min bleed-air flow rate and stoichiometric fuel flow.

The concentration of O_2, CO_2, and CO in the inert gas stream (after drying) is plotted in Figure 28 as a function of reactor peak temperature. As anticipated from consideration of temperature effects on reaction rates, the oxygen content of the inert gas stream drops significantly in the range from 1000° to 1300°F. Of interest here is the higher carbon monoxide content of the inert gas at higher temperature. This is consistent with thermodyamic equilibrium considerations; if much higher reactor temperatures were used, carbon monoxide would be formed preferentially to carbon dioxide.

The lower oxygen conversion at lower reactor peak temperature is the result of two effects: first, although the presence of the catalyst has a major effect on reaction kinetics, it remains that reaction rates will be directly proportional to reactor temperature. Second, at lower temperature (higher ram-air flow), the front portion of the reactor is chilled and the reaction front is displaced downstream by as much as 1 in. (see Figure 26). As a result, the effective size of the catalyst bed is reduced.

In terms of the limitations imposed upon reactor design by thermal stresses, designing the unit for peak temperatures of 1250° to 1300°F appears to be a reasonable compromise between structural and performance requirements.

g. Effect of Fuel-Air Ratio

Figure 29 is a plot of inert gas, O_2, CO_2, and CO concentration as a function of fuel-bleed-air ratio. The plot is for the baseline bleed-air flow of 1 lb/min and a fixed ram-bleed air ratio of 10:1. The stoichiometric fuel-air ratio data point was taken from Figure 28.

At lean fuel-air mixtures, CO_2 formation is favored and CO production is low. Although excess oxygen is available, which tends to promote fuel oxidation to CO, CO_2 formation is favored at the low-reactor temperatures corresponding to the plot of Figure 29. At rich fuel-air mixtures, the excess fuel has a very significant effect on the equilibrium of the competing reactions. Large quantities of CO are produced, as well as lower order hydrocarbons such as methane, ethane, ethylene, and also carbon and tars.

TEST CONDITIONS

1. BLEED AIR FLOW: 1.0 LB/MIN
2. FUEL/AIR RATIO: 0.068 (STOICHIOMETRIC)
3. RAM AND BLEED AIR INLET TEMPERATURE ≈ 450°F

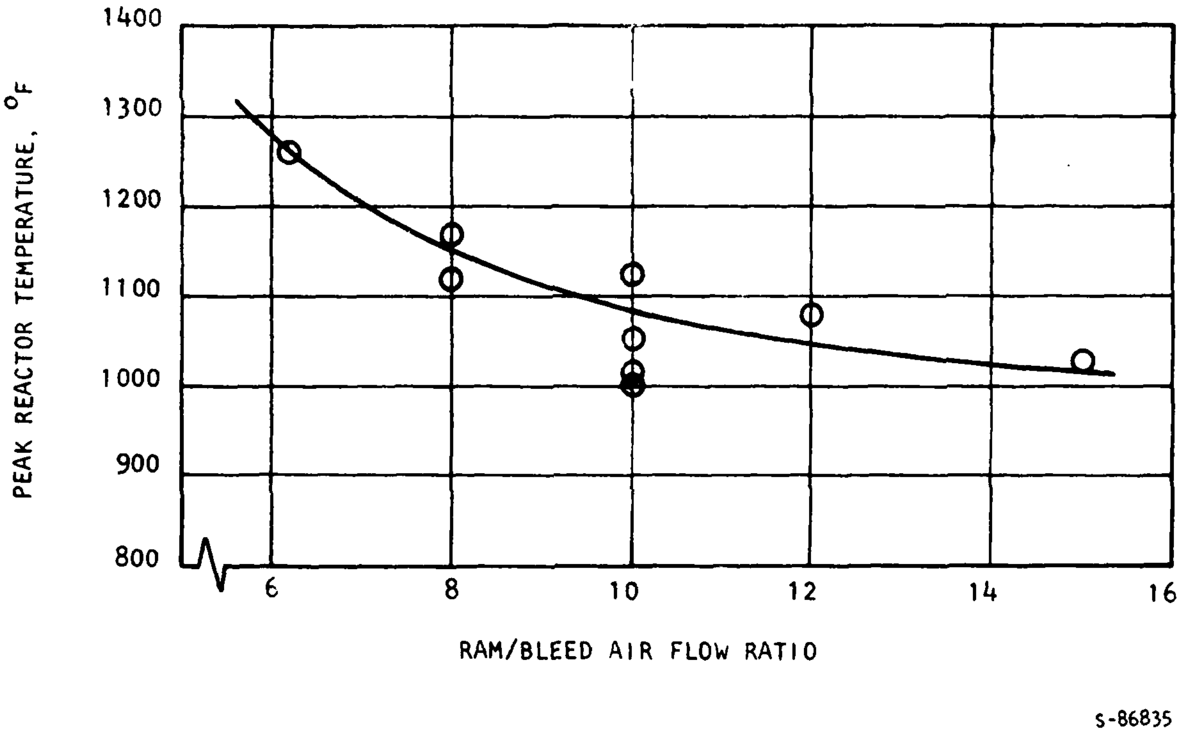

Figure 27. Effect of Ram Air on Reactor Temperature

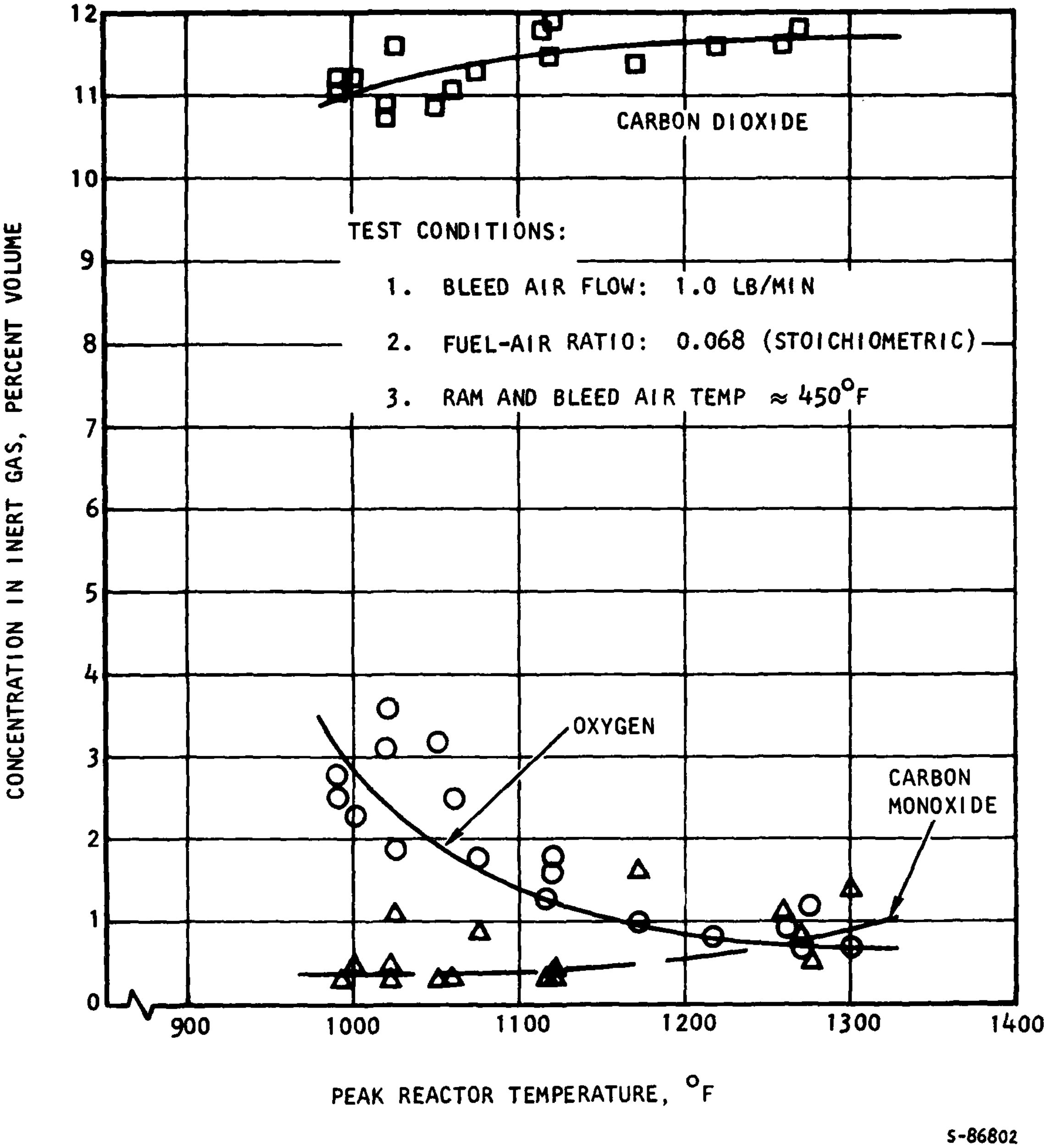

Figure 28. Effect of Reactor Temperature

TEST CONDITIONS

1. BLEED AIR FLOW: 1.0 LB/MIN

2. RAM-BLEED AIR RATIO: 10

3. RAM AND BLEED AIR TEMPERATURE $\approx 450^{\circ}F$

4. MAXIMUM REACTOR TEMPERATURE

DATA POINT			
1	$1020^{\circ}F$	4	$980^{\circ}F$
2	$1115^{\circ}F$	5	$1085^{\circ}F$
3	$1020^{\circ}F$	6	$920^{\circ}F$

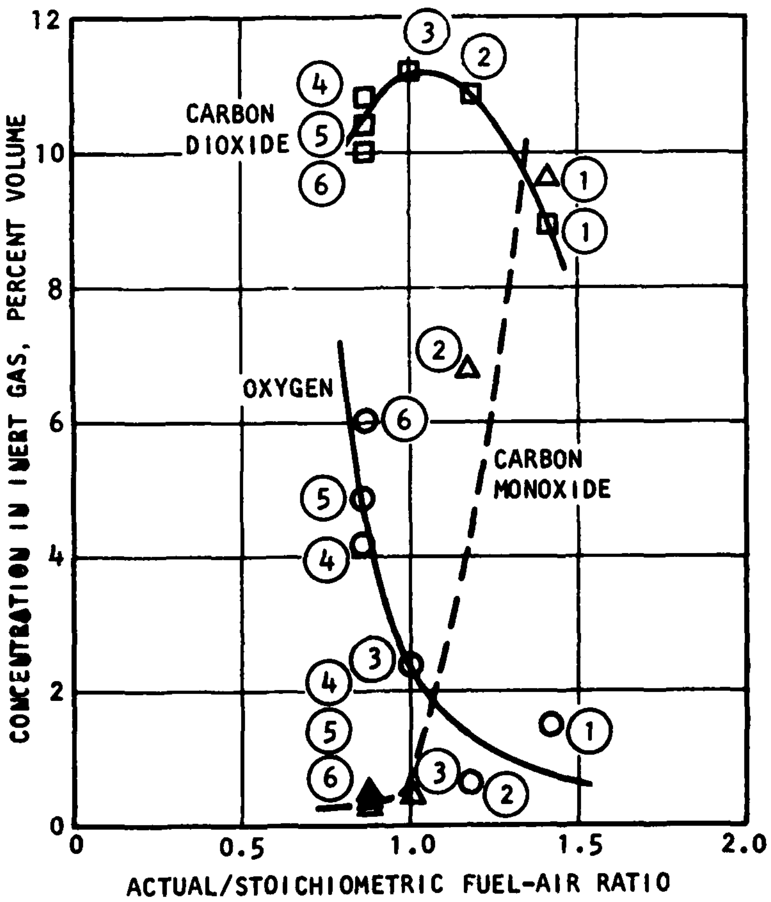

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Figure 29. Effect of Fuel-Air Ratio on Inert Gas Composition

To minimize production of tars and enhance production of inert CO_2, fuel flow control is highly desirable to provide a stoichiometric or slightly lean fuel-bleed-air mixture at reactor inlet.

h. Effect of Bleed-Air Flow

The effect of bleed-air flow on reactor performance was determined experimentally. Reactor temperature profiles are shown in Figure 30 for three bleed-air flows: 1.0, 1.5, and 2.3 lb/min. Stoichiometric fuel-air ratios were maintained through these runs. The ram-air flow through the reactor was adjusted to yield a reactor peak temperature of 1300°F. The three test runs shown are identified in Table VII as 30, 32, and 35. The following effects are noted:

(1) Higher bleed-air flows result in slightly higher overall temperatures over the high activity portion of the unit. The much higher temperature differences in the downstream half of the unit are attributed primarily to cooling air flow distribution problems that occurred as a result of reactor damage sustained toward the end of the test program.

From the data, it is apparent that the high heat fluxes generated within the catalyst bed can be accommodated using the particular heat transfer surfaces of the prototype reactor.

(2) The flame arrestor temperature was maintained at the 450°F level under all conditions.

(3) A ram-to-bleed-air flow ratio of about 6:1 will maintain reactor peak temperature at 1300°F over the entire bleed-flow range investigated. As a result, the ram-air penalty is the same for all conditions.

(4) The reaction front and the temperature peak occur at about the same point in the catalyst bed.

As the fuel-bleed-air flow rate is increased over the catalyst bed, space velocity will increase accordingly and the reactor effectiveness is expected to drop. This effect is shown in Figure 31. The data are presented for a peak reactor temperature of 1300°F and operation at stoichiometric fuel-air ratios. Increasing the space velocity results in incomplete combustion to CO_2 and formation of increasing quantities of carbon monoxide with attendant heavy hydrocarbons, tars, and carbon.

The catalyst charge of the breadboard reactor is 33.4 cu in. Since the size and weight of the flight unit will be roughly proportional to the space velocity, there is a strong incentive to design the flight reactor for higher space velocity. Note that the 2-percent inert gas-oxygen concentration obtained at an approximate flow of 2.1 lb/min is well below the 9-percent oxygen-content inert-gas mixture that is acceptable as an upper limit.

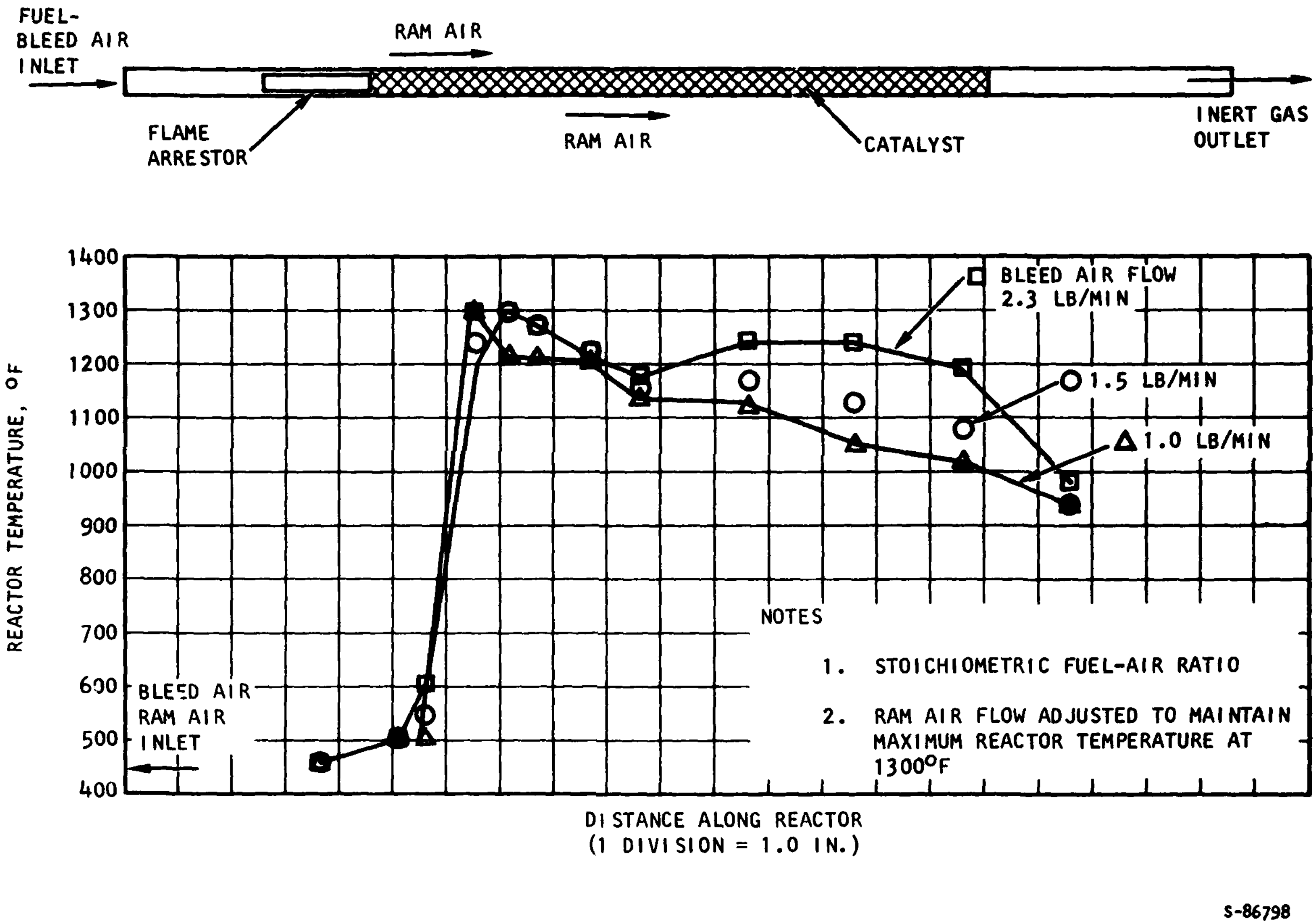


Figure 30. Effect of Bleed Air Flow on Reactor Temperature Profile

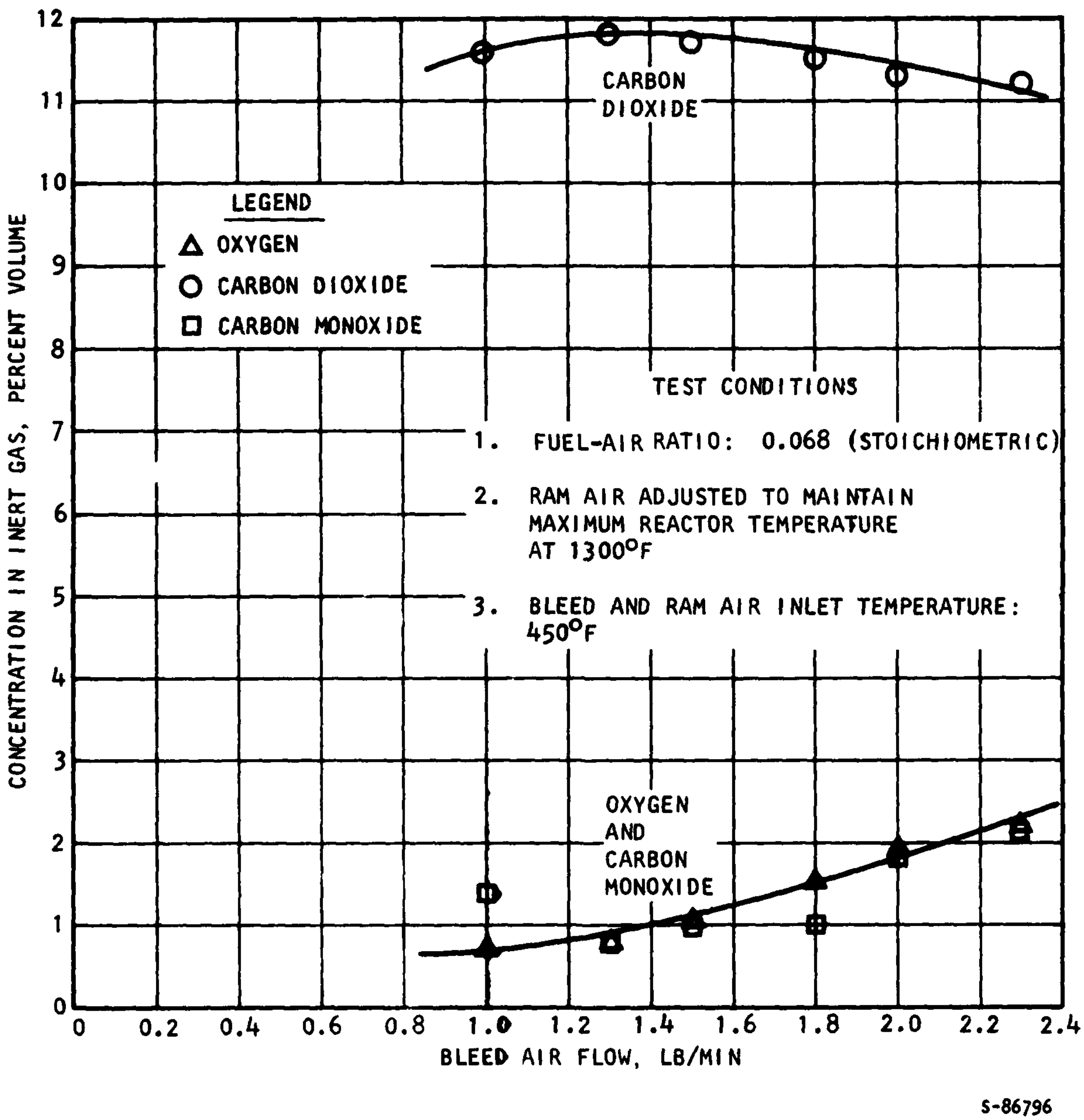


Figure 31. Effect of Bleed Air Flow on Performance

Final selection of a space velocity will be based on two major considerations: (1) reactor weight, which dominates the weight of the system; and (2) the problems associated with formation of heavy hydrocarbons and tars, and the techniques employed to prevent their entrainment into the inerting system equipment and fuel tanks.

i. Startup Characteristics

Both the high- and low-flow reactors of the fuel tank inerting system will be operated at constant bleed-air and fuel flows; the ram-air flow will be controlled to provide a fixed heat sink relative to the reactor heat load and operating temperature. The only significant transient mode of operation, in terms of the reactor itself, is startup. Throughout the reactor test program, successful startups with any of the tested reactor configurations occurred very rapidly, and reactor temperatures stabilized within 3 or 4 min of the start of fuel injection into the bleed-air stream.

A typical temperature buildup during the starting transient is shown in Figure 32. In the breadboard reactor, the first step in the starting sequence was to bring the reactor temperature to 450°F by flowing bleed- and ram-air at that temperature through the unit. Once the catalyst bed reached 450°F, fuel oxidation occurred over the platinum catalyst mixed with the Code A catalyst. The platinum catalyst accounted for 5-percent by volume of the total catalyst charge. As heat was released, the Code A catalyst became increasingly active and the reaction rate increased rapidly, as indicated by the plot of Figure 32.

This startup technique, using platinum catalyst, was found to be unacceptable for a flight reactor because of the rapid rate of poisoning of the platinum that probably was due to the presence of sulfur in the fuel. After several hours of running (about 12 hr) with the same catalyst bed, normal startup (as depicted in Figure 32) could not be achieved, and the reactor had to be reloaded. Typically, the following phenomena occurred when startup was attempted with spent platinum catalyst:

(1) Startup could not be effected.

(2) Startup occurred only on one side of the bed. This was evidence of high temperatures along one row of thermocouples, while the other row of thermocouples showed no temperature rise. Under these conditions, unreacted fuel-air comes in contact with hot gases at the reactor outlet with potential combustion downstream of the bed.

(3) Startup occurred across the catalyst bed, but at a location near the bed outlet. In this case, the reaction started in the bed and was completed outside of it.

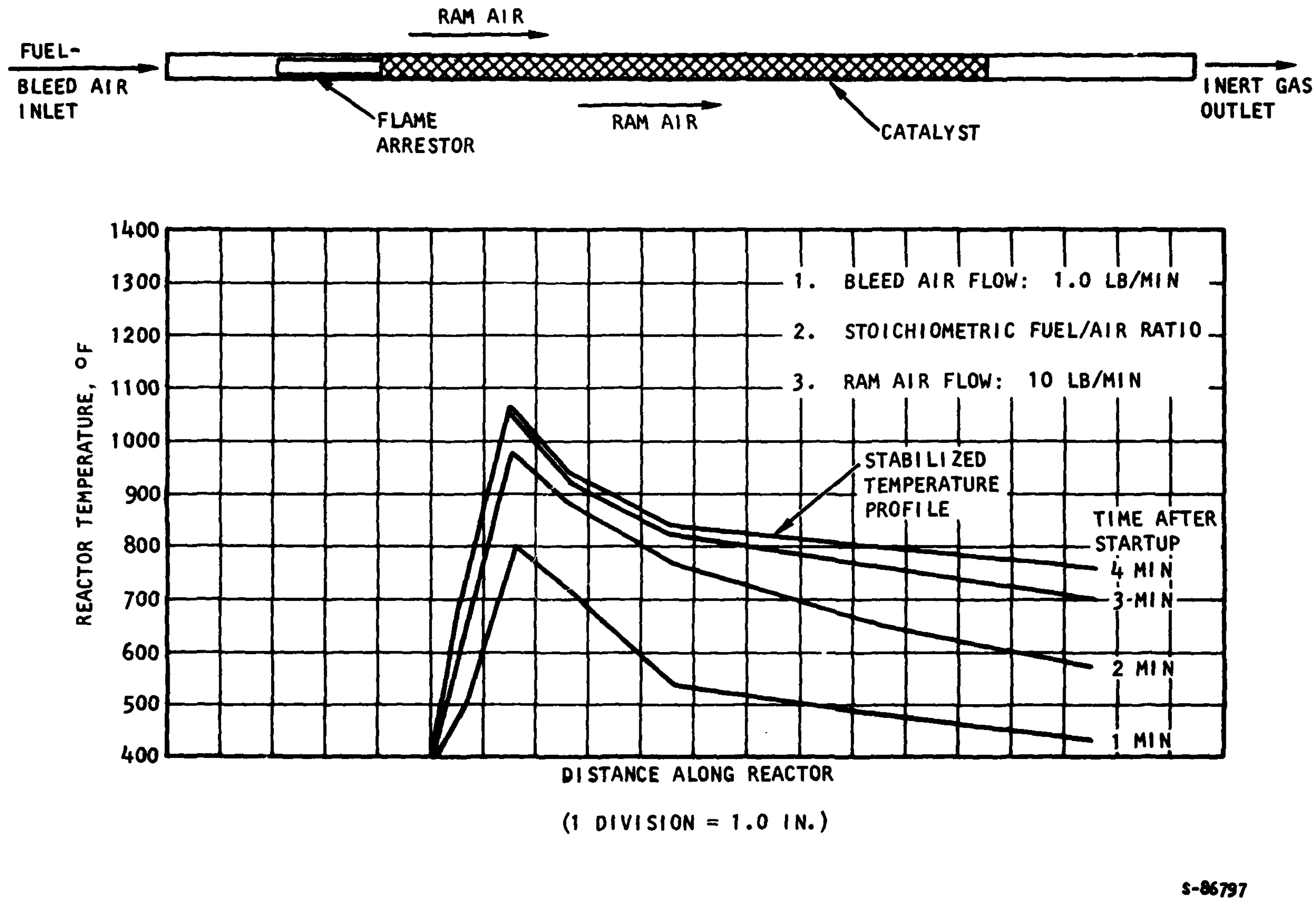


Figure 32. Typical Reactor Temperature During Start

As mentioned previously, this situation was remedied by reloading the bed with fresh platinum catalyst. No startup problems were encountered with new charges. In a flight reactor, initial catalyst bed heating to 700° or 800°F will be effected by electrical heaters. At this temperature, the Code A catalyst is self-starting and no startup problems are anticipated.

j. Reactor Products

The reactor outlet stream was monitored continuously through the test program to determine the concentrations of oxygen, carbon dioxide, and carbon monoxide. These data are listed in Table VII. Experience gathered previously had shown that low concentrations of oxygen and carbon monoxide were directly related to the effectiveness of the oxidation process toward the desired end products: CO_2 and H_2O. Also, when operating at high effectiveness, only minimal quantities of hydrocarbons were found in the product gas stream.

A gas sample from the prototype module was analyzed for hydrocarbon contents. The data are as follows:

Constituent	Concentration, % vol
Oxygen	0.5
Carbon dioxide	12.7
Carbon monoxide	0.9
Hydrocarbons	0.017

As shown, only a very small quantity of unreacted hydrocarbons remain in the gas stream under conditions of low oxygen and low carbon monoxide content (see run 27). This represents a significant improvement in the overall effectiveness of the reaction by comparison to data obtained previously.

Gas samples from runs 36, 37, and 38 of Table VII were analyzed specifically for the presence of sulfur dioxide. Mass spectrometry indicated SO_2 levels below 0.05 percent by volume. Further analyses by flame photometric detection showed that the CO_2 concentration in the reactor product gases was less than 10 ppm by volume.

Several water samples were taken and analyzed for tar content and pH. Water pH was between 1.85 and 3.7, probably due to formation of significant quantities of SO_2 in the reactor. Results of analyses of the water, obtained from runs 37 and 38 (Table VII), for presence of sulfur are presented in Table IX. The sulfur content of the JP-4 fuel used during these runs was determined experimentally to be 0.27 percent by weight. This very high fuel sulfur content is considerably in excess of the maximum 0.15-wt percent specified for JP-4. Lower fuel sulfur content would result in less acidic product water. This established the requirements for elimination of SO_2

TABLE IX

ANALYSIS OF PRODUCT WATER

	Run 37 (Table VII)	Run 38 (Table VII)
Sulfate, gr/liter	1.34	1.02
pH measured	2.1	2.2
pH calculated*	1.6	1.7

* Assuming all sufate present as H_2SO_4

at reactor outlet to prevent corrosion of the system equipment and also the aircraft fuel tank materials. Material corrosion tests conducted under this program are described in the following section of this report.

The presence of tars in the water condensed from the reactor outlet stream is indicative of polymerization of a portion of the fuel. It appears that the Code A catalyst favors this phenomenon.

Observations made through the entire development program indicate that the rate of tar formation is directly related to the excess fuel in the reactor inlet mixture and also to the effectiveness of the reaction as measured by oxygen content of the reactor product stream. When operating at near-stoichiometric fuel-air ratios, tar production was reduced considerably in comparison with operation at fuel-rich mixtures.

In the series of tests with the prototype reactor, operation was predominantly at stoichiometric fuel-air ratios. Under these conditions of minimal tar formation, it was found that the tars were removed from the system with the condensate and did not accumulate within the inert gas passages or the condensate collection plenum of the condenser. Water samples taken during runs 30 and 31 of Table VII showed tar contents of 0.2 and 0.12 percent.

Here it is suggested that further exploratory testing be conducted to completely assess the tar formation problem prior to designing equipment for its removal or accommodation. Possibly operation under slightly lean or rich fuel-air ratio may suppress tar formation considerably.

7. CONCLUSIONS

The development program described in this section was very successful in validating the approach selected for the design of a flight-configured reactor of a reasonable size, and in the generation of parametric design data which can be used to optimize the design of a flight unit. The following are major test program achievements:

a. High oxidation reaction effectiveness to CO_2 and H_2O was achieved.

Inert gas oxygen concentrations below 2 percent were achieved consistently at stoichiometric fuel-air ratios.

b. Techniques were developed to control the reaction within the catalyst bed at relatively low temperature.

c. The configuration of the extended heat transfer surfaces used for catalyst bed temperature control were demonstrated as very effective for this purpose. No extreme temperature peaks were experienced.

d. The design and construction of the reactor was successful in accommodating thermal stresses involving temperature gradients on the order of 400°F/in. in the longitudinal direction. Reducing material thickness to reduce weight should alleviate thermal stress problems.

e. Analysis of the contaminants contained in the inert gas from the reactor establishes the requirements for a sorbent bed for absorption of the acid compounds (SO_2 as a major constituent). The presence of tars in the reactor effluent need to be investigated further.

It should be noticed that these achievements were realized through progressive testing of the laboratory unit and of the 1-lb/min and 6-lb/min units through the prototype module. Although most of the significant design data were obtained specifically from testing of the prototype module, a great deal of information leading to this series of successful tests was derived from prior testing of the other units.

Reactor parametric performance data were presented in the discussion of the prototype reactor test program. The following listing summarizes reactor operating parameters which have been shown to yield high reactor effectiveness as expressed by the inert gas low content of oxygen and carbon monoxide. These data form the basis for the design of the flight reactor and the complete fuel tank inerting system:

Bleed-cooling-air flow pattern	Parallel
Fuel-bleed-air ratio	Stoichiometric
Cooling- to bleed-air ratio	5:1 to 6:1
Cooling- and bleed-air temperatures at reactor inlet	450°F
Space velocity	25,000 hr^{-1} (50,000 hr^{-1} max.)
Operating pressure	45 psia

Operation at these conditions will result in generation of inert gas with an oxygen concentration lower than 1 percent. Also, the production of tars will be minimized.

SECTION IV

TANK MATERIALS CORROSION TESTS

1. OBJECTIVES

Jet fuels contain sulfur that will oxidize to SO_2 in the inerting system catalytic reactor. While most of the SO_2 formed will be dissolved in the water condensed in the system downstream of the reactor, small quantities will be entrained into the fuel tanks with the inert gas. As part of the program, a series of tests were conducted to (1) determine the corrosive effect of SO_2 on fuel tank materials of construction, and (2) provide basic data for the design of SO_2 sorption beds if required.

2. SCOPE

The test program covered three material categories:

- Bare metals

  Aluminum 7075-T6

  4130 Steel

  Stainless steel 304

  6Al-4V titanium

  Aluminum 7075-T6 coupled with stainless steel 304

- Coatings--per MIL-C-27725 procured from Products Research and Chemical Corp., Burbank, California, as PR-1560MC

- Sealants

  PR 1422

  Proseal 890 B-2, Teledyne Coast Proseal Co., Compton, California

  Dow Corning 94-002, Midland, Michigan

3. TEST PROCEDURE

The test samples (0.040 by 2-7/8 by 6 in.), either bare or coated with the materials listed above, were exposed to a 3-phase media of air/JP-4 fuel/aqueous solution. The pH of the aqueous solution varied from 2 to 6 and was adjusted by addition of SO_2. Sulfur content of the fuel was raised to 0.15 percent by weight by the addition of t-dibutyl disulfide.

a. Bare Metal Tests

Samples of each bare metal were subjected to the following environments for 7 days at 140°F:

Aqueous Solution	Fuel
Water	MIL-T-5624G, Grade JP-4
SO_2, pH = 2	MIL-T-5624G, Grade JP-4
SO_2, pH = 3	MIL-T-5624G, Grade JP-4
SO_2, pH = 4	MIL-T-5624G, Grade JP-4
SO_2, pH = 5	MIL-T-5624G, Grade JP-4
SO_2, pH = 6	MIL-T-5624G, Grade JP-4

Figure 33 shows six resin kettles in a temperature controlled oven. The six kettles contain different test solutions so the entire series of tests listed above could be conducted simultaneously for each material investigated. Each resin kettle contained one test panel. All corrosion testing was conducted in the test setup shown.

At the completion of the bare metal corrosion test, the samples were rinsed in acetone and visually examined for signs of corrosion. The weight of the test panels was recorded before and after the test to determine weight change as a result of corrosion. Also, the pH of the aqueous solutions was measured before and after each test.

b. Tank Coating Material Tests

Corrosion testing of the MIL-C-27725B fuel tank coating was conducted on panels of the same dimensions as the bare metal tests. The same apparatus and procedures were used.

Eleven 0.040- by 2-7/8- by 6-in. conversion-coated aluminum (7075-T6) panels were dipped in the coating and allowed to drain. After the standard cure, each panel was separately exposed to the triphase environment (aqueous solution/JP-4 fuel/air) at 140°F for 5 days. The water-phase composition ranged from pH 2 to pH 6 in 1-pH unit increments with and without 3 percent NaCl added, plus one solution that was also 5 percent acetic acid (pH 2.35) and 3 percent NaCl per MIL-C-27725B, para. 4.7.19. The liquid-phase compositions investigated are defined as follows:

	Distilled Water Solution	Fuel
(1)	3-percent NaCl solution with acetic acid per MIL-C-27725B (ASG;	Reference fluid
(2)	SO_2, pH 2	MIL-T-5624G, Grade JP-4

Figure 33. Corrosion Test Apparatus

(3)	SO_2, pH 2, 3-percent NaCl solution	MIL-T-5624G, Grade JP-4
(4)	SO_2, pH 3	MIL-T-5624G, Grade JP-4
(5)	SO_2, pH 3, 3-percent NaCl solution	MIL-T-5624G, Grade JP-4
(6)	SO_2, pH 4	MIL-T-5624G, Grade JP-4
(7)	SO_2, pH 4, 3-percent NaCl solution	MIL-T-5624G, Grade JP-4
(8)	SO_2, pH 5	MIL-T-5624G, Grade JP-4
(9)	SO_2, pH 5, 3-percent NaCl solution	MIL-T-5624G, Grade JP-4
(10)	SO_2, pH 6	MIL-T-5624G, Grade JP-4
(11)	SO_2, pH 6, 3-percent NaCl solution	MIL-T-5624G, Grade JP-4

After the exposure, scribe lines 1-in. apart were made through the coating in each different phase-exposed section. Tape (3M 250) was pressed firmly over the coating and ripped off in one swift motion to determine coating adherence and to detect corrosion under the coating.

c. Tank Sealer Tests

Each of the three tank sealers were tested per MIL-S-8802, para. 4.5.10. The sealers were applied to six aluminum 7075-T6 panels (2-7/8 in. wide by 6 in. high by 0.040 in. thick) in the form of duplicate strips 3/4 in. wide by 5 in. high by 1/8 in. thick. An overcoating per MIL-S-4343 was applied over the polysulfide sealants (PR 1422 and Proseal 890 B-2). After the standard 14-day room temperature cure, the test coupons were exposed to the aqueous/JP-4/air triphase mixture for 20 days at 140°F. The aqueous-phase pH range and NaCl content for each test sample are defined below:

	Distilled Water Solution	Fuel
(1)	3 percent NaCl	Test fluid
(2)	SO_2, pH 2, 3-percent NaCl	MIL-T-5624G, Grade JP-4
(3)	SO_2, pH 3, 3-percent NaCl	MIL-T-5624G, Grade JP-4
(4)	SO_2, pH 4, 3-percent NaCl	MIL-T-5624G, Grade JP-4
(5)	SO_2, pH 5, 3-percent NaCl	MIL-T-5624G, Grade JP-4
(6)	SO_2, pH 6, 3-percent NaCl	MIL-T-5624G, Grade JP-4

The pH of the solutions were adjusted by addition of SO_2 gas.

After the test, each test panel was visually inspected for evidence of corrosion under the sealer.

4. TEST RESULTS

a. Bare Metals

Table X summarizes the test results. All observations are applicable to the aqueous layers. No corrosion was observed in the fuel or air layers.

Aluminum and 4130 steel are unacceptable unless a suitable coating is applied to the surface of the tank. Figure 34 shows the six aluminum samples after the test. The dark part of the sample exposed to the aqueous solution shows signs of heavy corrosion.

Testing of the aluminum-steel that was coupled by means of cadmium-plated bolts indicate that cadmium is unacceptable as a coating material.

Titanium appears to be the only metal that was corrosion-resistant over the entire range of test conditions investigated. Stainless steel 304 may be satisfactory; however, other stainless alloys such as 316, 321, or 347, should be considered in lieu of 304.

b. Coatings

Fuel tank coating PR-1560 MC obtained from Products Research and Chemical Corp. passed the corrosion test except at very low pH (2 and 3). After exposure to an aqueous SO_2 solution with a pH of 2, coating delamination occurred when subjected to the tape peeling test described above. Coating delamination was also observed to a lesser degree after immersion in the 3-percent NaCl-pH 3 aqueous SO_2 solution. In this case, about eight small blisters (less than 1-mm dia) were observed after the peeling test. All other areas in all other solutions passed MIL-C-27725B requirements.

This coating appears satisfactory for fuel tank application.

c. Sealer Materials

The three sealer materials tested (PR 1422, Proseal 890 B-2, and Dow Corning 94-002) passed the corrosion test. No sign of corrosion was observed on any of the test panels subjected to the test conditions described above.

5. CONCLUSIONS

Based on the result of the susceptibility tests, it appears that damage from corrosive products generated by the inerting system may be eliminated by proper material selection and coating treatment. However, corrosion protection of the inerting system equipment itself may be necessary and desirable to minimize weight through the use of aluminum for the fabrication of the low-temperature components.

TABLE X

BARE METAL CORROSION TEST DATA

Metal	pH Start	pH Finish	Weight Change in $mg/cm^2/week$	Remarks
7075-T6 Aluminum	6.9	5.2	+0.10	General corrosion
	6.0	5.4	+0.22	General corrosion
	5.0	5.5	+0.23	General corrosion
	4.0	5.8	+0.25	General corrosion
	3.0	5.4	+2.44	General corrosion
	2.0	4.6	+0.15	Numerous small pits
4130 Steel	6.8	5.6	-1.48	Light brown oxide
	6.0	5.4	-1.69	Light brown oxide
	5.0	5.0	-1.31	Snowflake pitting in air layer, brown oxide in aqueous solution
	4.0	5.15	-1.47	Heavy brown oxide
	3.0	4.75	-3.34	Light pitting in air layer, heavy brown oxide in aqueous solution
	2.0	4.8	-1.74	Entire panel corroded, dark brown corrosion in aqueous solution
304 Stainless	7.0	4.8	<+0.01	Pitted at fuel-water interface
	6.0	5.6	<+0.01	No change
	5.0	4.8	<+0.01	No change
	4.0	4.2	No change	No change
	3.0	2.8	No change	One pit at fuel-water interface
	2.0	3.7	-1.82	Severe pitting corrosion
6Al-4V Titanium	6.9	3.9	No change	Slight stain
	6.0	3.9	No change	Light brown discoloration
	5.0	4.0	No change	Light brown discoloration
	4.0	3.6	No change	Brown oxide
	3.0	2.8	No change	Blue-brown oxide
	2.0	1.8	+0.01	Blue oxide in fuel and water layer
7075-T6 Aluminum Stainless Steel Couple	6.9	6.9	+1.85	General aluminum corrosion
	6.0	8.4	+1.00	General aluminum corrosion
	5.0	8.1	+0.60	General aluminum corrosion
	4.0	8.9	+1.29	General aluminum corrosion
	3.0	6.4	+0.57	Cadmium plate is pitted
	2.0	5.9	+3.49	Orange rust deposits on aluminum stainless steel has about two dozen small pits. Cadmium is corroded away.

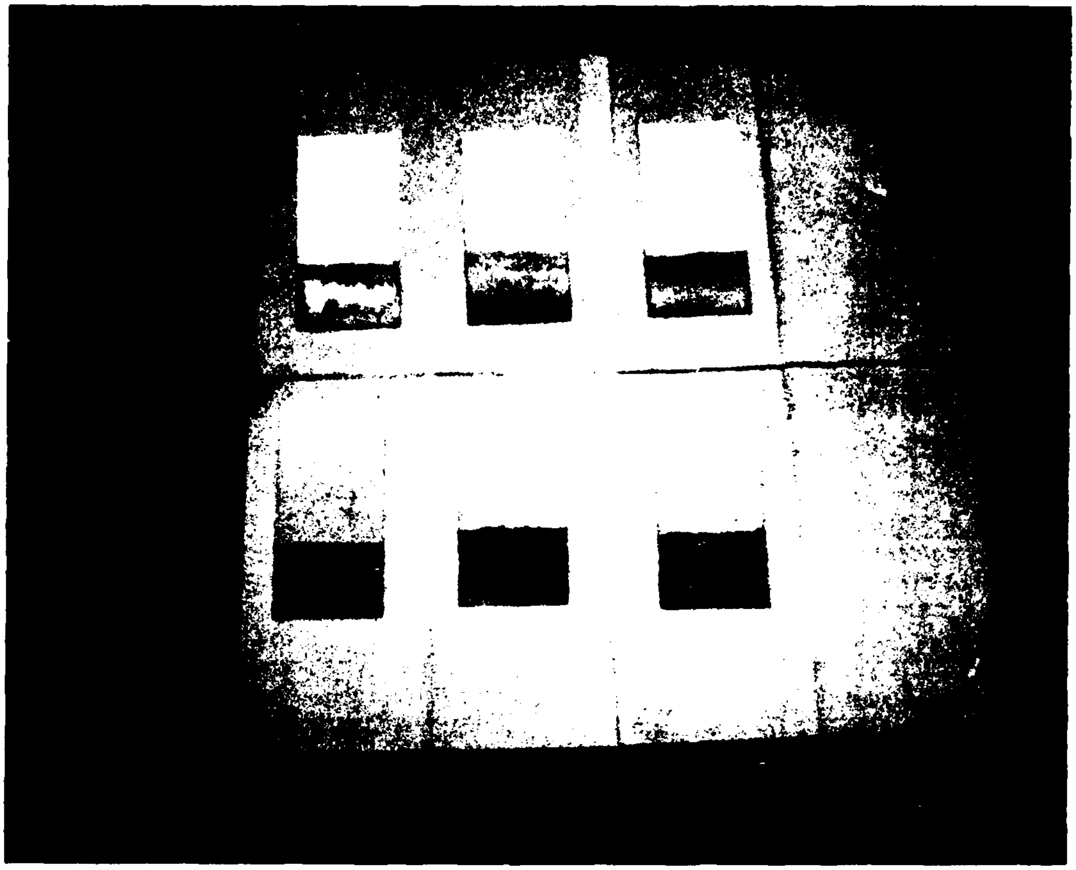


Figure 34. Aluminum Panels After Triphase Corrosion Test

Because of the wide variety of compounds that can contain sulfur in the liquid fuel, removal of the sulfur from the liquid is impractical, if not impossible, in a system such as the one considered here. In the combustion reaction, the sulfur compounds will be oxidized and SO_2, which can easily be removed from the reactor exhaust, will be formed.

Depending on the reactor operating conditions and also on the flow configuration through the reactor (counter or parallel flow), the reactor product gas temperatures could be as high as 900°F (see discussions of reactor performance presented in Section III).

Preliminary investigation of candidate sorbents with capability for SO_2 absorption at high temperatures revealed that manganese dioxide, MnO_2, is about optimum for this purpose. SO_2 removal is effected according to the reaction

$$MnO_2 + SO_2 \rightarrow MnSO_4 \tag{3}$$

Formation of the sulfate appears compatible with the inert gas composition and temperature at reactor outlet. The dioxide will not react with the carbon monoxide as the carbon dioxide formed in the reactor at temperatures from 400° to 900°F. At reactor outlet conditions of 45 psia, the partial pressure of sulfur dioxide will be 2.8 by 10^{-4} atm, assuming that the fuel contains 0.15-percent sulfur and that the oxidation reaction proceeds stoichiometrically to CO_2 and water. At 900°F, the equilibrium partial pressure of sulfur dioxide in reaction (3) above is 7.4 by 10^{-4} atm, indicating that a very high proportion of sulfur dioxide will be removed from the inert gas. About 0.6 by 10^{-4} lb of SO_2/lb of inert gas will be entrained to the fuel tank after scrubbing through a manganese dioxide sorbent bed.

In terms of a typical bomber mission, it is estimated that a 10-lb bed of manganese dioxide would be required for 500-hr operation. Note here that the average jet fuel sulfur content should be considerably lower than the 0.15 percent maximum specified.

It is recommended that a manganese dioxide sorbent bed be incorporated in the system for SO_2 removal. This bed should be designed for 500-hr operation and should be located immediately downstream or within the outlet passages of the catalytic reactor.

In view of the very low SO_2 flow to the fuel tank, it appears that the 304 stainless steel (or better alternates) and all coating and sealant materials investigated are suitable for fuel tank fabrication.

SECTION V

SYSTEM DESIGN CONSIDERATIONS

1. SYSTEM AND REACTOR PROCESS FLOWS

The system must be sized for production of inert gas at a rate satisfying the flow demands of the aircraft over the entire range of operating conditions. Examination of the data of Figure 3 shows that the inert-gas flow range required varies from 0 to 52 lb/min. Further, during a typical mission, inert gas flow rates of less than 0.5 lb/min will maintain tank pressure for a majority of the total mission time. The high-flow requirements correspond to tank sparging and descent.

Designing the system and its components for a turndown ratio of the magnitude required to cover this flow range is, in practice, very difficult if not impossible. The design of valves to maintain fuel-air ratios and system pressure with any kind of accuracy is not practical unless two-stage type control valves are used throughout. Furthermore, operation of the reactor over the range (from a fraction of 1-lb/min to over 50-lb/min) is not practical because of the requirements for high fuel-bleed air mixture velocities (50 to 100 ft/sec) through the flame arrestor. Also, should a single reactor be sized to handle the high flow requirements, severe problems of flow distribution will exist on both the bleed-fuel side and the cooling air side of the unit. Under such conditions temperature control may be possible.

To obviate potentially significant development risks and simplify system controls, a dual-flow system appears optimum and is recommended. Overall system flow rates and gas composition in the low and high flow modes of operation are depicted in Figure 35.

a. Low-Flow Mode

In the low-flow mode of operation, a small reactor is used for production of inert gas at a constant rate of 0.5 lb/min. This flow rate will be adequate for tank pressurization over 90 percent of mission time. The bleed air and fuel flows are controlled by means of fixed orifices and reactor operating conditions are constant. Fuel tank pressure is controlled by dumping excess inert gas overboard or by bleed air makeup if inert gas production is inadequate. The makeup valve is orificed to limit bleed air flow to the inert gas stream. In this manner, the maximum oxygen concentration of the inert gas stream is limited to 9 percent.

The space velocity through the reactor is maintained at 22,260 hr^{-1} corresponding to a 1 lb/min bleed-air flow through the breadboard reactor. At that space velocity, experimental data presented in Figure 31 show that the oxygen content of the reactor outlet gases is 0.7 percent. This provides a margin in the design of the unit. Using the same catalyst bed module as that used for the prototype unit (see Figure 25), only one module will be required to handle the 0.5-lb/min load.

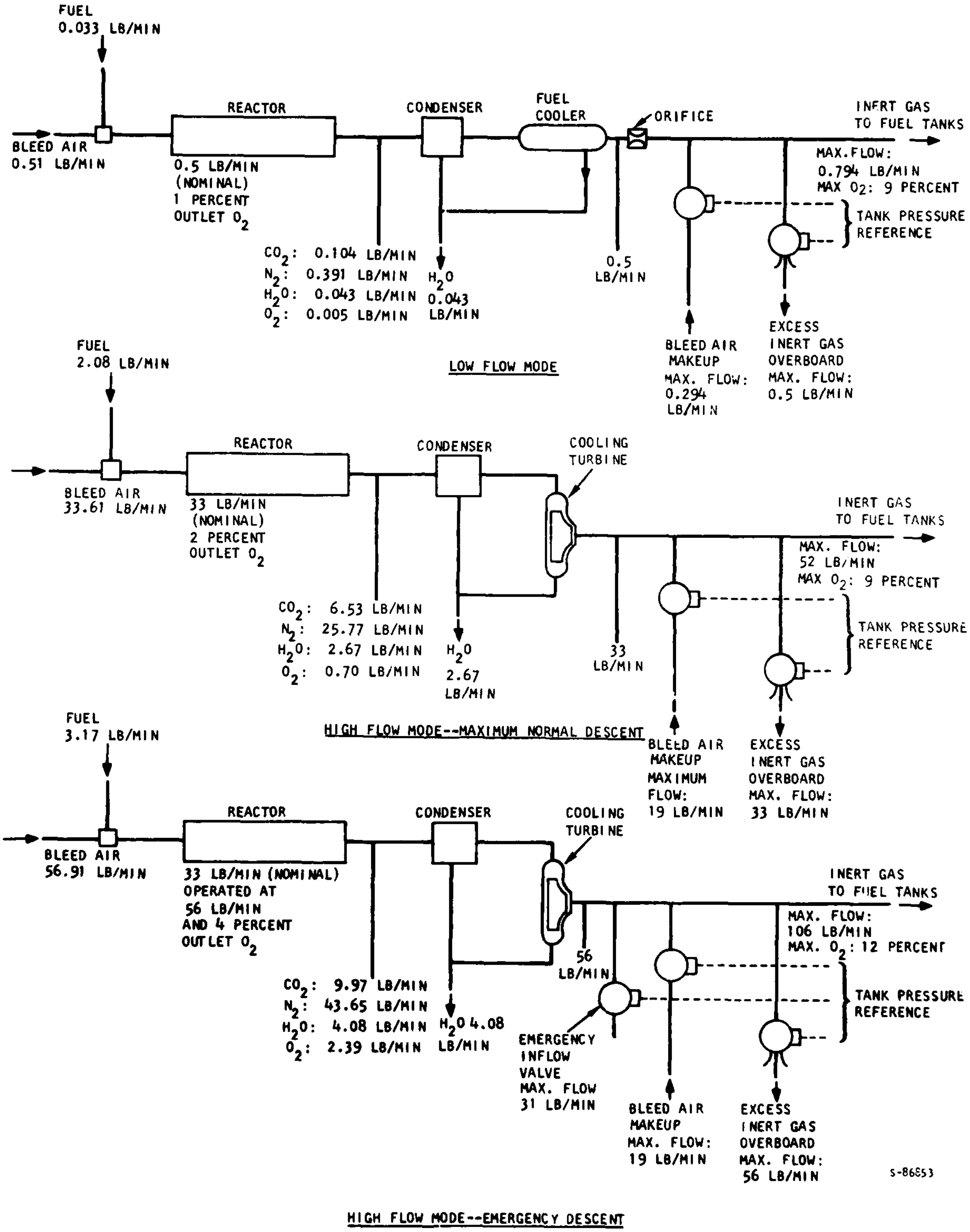


Figure 35. Inerting System Flows in Various Flight Modes

Reactor pressure is maintained at 45 psia by an orifice upstream of the flow control valves.

Moisture removal is effected by condensation in a ram air cooler-condenser. Adequate ram-air flow is available under normal conditions to drop the temperature of the product gases to about 60°F. During high-speed flight conditions, the temperature of the ram air can exceed the maximum temperature of 200°F specified for the inert gas supply. A fuel cooler downstream of the cooler-condenser is then used for gas temperature and moisture control. Moisture feed to the tank is discussed in more detail later.

b. High-Flow Mode

In the high-flow mode of operation, corresponding to maximum normal descent at the rate of 4000 to 5000 ft/min, the fuel tank pressurization flow requirements will increase as the aircraft altitude decreases. Maximum flow demand is 52 lb/min at sea level. A plot of flow requirements is given in Figure 4 as a function of altitude.

The reactor process flow and weight can be reduced considerably by mixing bleed air with the inert gas from the reactor so the oxygen concentration of the gas delivered to the fuel tanks reaches 9 percent under maximum flow conditions. At lower flow requirements, as for fuel tank sparging, no mixing will be required and the output from the reactor will be fed to the tank at an oxygen concentration below 4 percent as specified.

The high-flow reactor is, by far, the heaviest component of the inerting system. Optimization of its weight requires careful consideration of all parameters influencing design. Among these are:

(1) Inert gas O_2 concentration--Data given in Figure 30 shows that higher flows processed in a given reactor size will result in higher output oxygen concentration. For the maximum normal descent, a total flow rate of 52 lb/min with bleed-air mix is used to yield 9 percent O_2 concentration. The reactor process flow is only a mild function of the reactor output O_2 content. This relationship is shown in Figure 36. Also plotted is the reactor weight corresponding to the O_2 concentrations and process flow shown. Note that reactor weight increases very rapidly at O_2 concentrations below about 2 percent.

(2) Inert gas composition--As discussed in Section III of this report, higher reactor oxygen contents are indicative of incomplete fuel oxidation in the catalytic bed. In turn, this results in the formation of increasing quantities of tars and carbon which are detrimental to long-life operation of the reactor itself and also to the system equipment downstream of the reactor. For this reason, oxygen concentrations above 2 to 3 percent are undesirable.

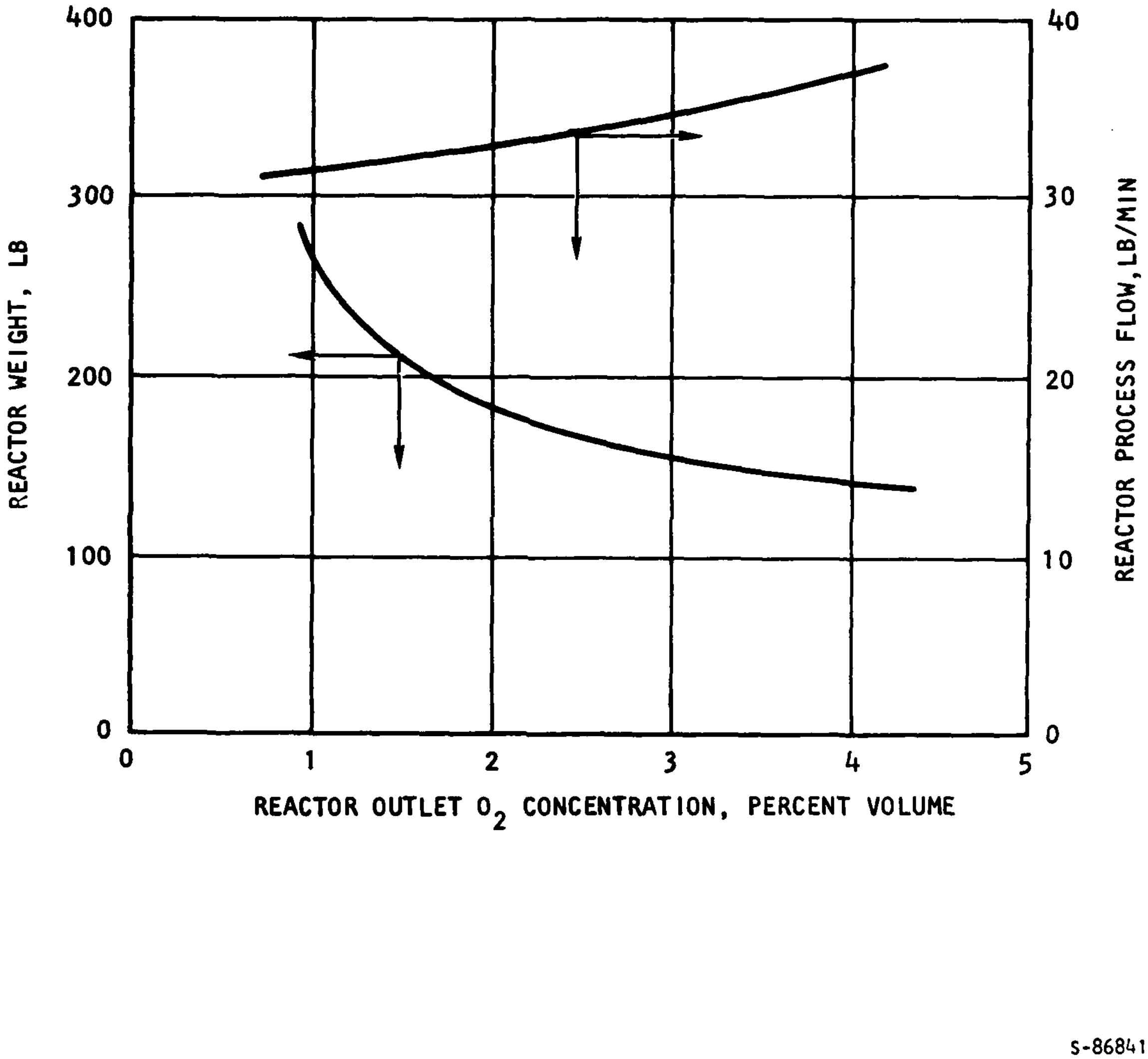


Figure 36. High Flow Reactor Parametric Data

(3) Provision for fuel tank inerting in emergency descent--As discussed below, a reactor designed for a steady-state inert gas production of 33 lb/min with an output O_2 concentration of 2 percent can also accommodate the emergency descent inert gas requirements. This constitutes a weight saving of about 90 lb by comparison to a separate Halon gas source for emergency situations.

In view of the above considerations, reactor design flow is selected as 33 lb/min with an O_2 output concentration of 2 percent.

Referring to Figure 35, it can be seen that the general arrangement of the high-flow circuit is similar to the low-flow circuit. The reactor is operated at constant flow. Valves are provided to maintain tank pressure through bleed-air fed into the inert gas stream or through overboard dumping of the system excess capacity. The flow capacity of these valves is about 65 times that of the corresponding low-flow circuit components. In this circuit, reactor pressure will be maintained by the cooling turbine inlet nozzles. The cooling turbine supplements the condenser capacity; condensation occurring in the expansion process yields a very low inert gas dew point.

c. Maximum Normal Descent

The system flow characteristics during maximum normal descent with empty fuel tanks is shown in Figure 37. Assuming that the fuel tank O_2 content is 2 percent at start of descent, the reactor will furnish an excess of inert gas from altitude to 6,500 ft. The excess gas will be dumped overboard. Below 6,500 ft, the overboard vent valve will close and the bleed-air makeup valve will open because the reactor outflow is insufficient to maintain tank pressure. As a result, the oxygen content of the inert gas delivered to the fuel tanks will increase rapidly from 2 percent to the 9-percent maximum level. It is of interest to note that at the end of the descent the average oxygen concentration of the gas contained in the tank is below 3 percent.

d. Emergency Descent

Two approaches were considered for emergency descent: (1) increasing the process flow through the high-flow circuit and (2) incorporating a separate Halon 1301 supply.

The quantity of Halon necessary to provide a 6-percent concentration in a volume corresponding to 80 percent of the tank capacity is 85 lb. The total weight of the charged Halon container is estimated at 120 lb. A tank of reasonable proportion would be 15 in. dia by 23 in. long for a total volume of 1.93 cu ft. This constitutes a sizeable weight and volume penalty.

By comparison, the high-flow circuit can be used at off-design point and will satisfy the requirements of the emergency descent case. The performance of the 33-lb/min, 2-percent O_2 reactor at a process flow rate of

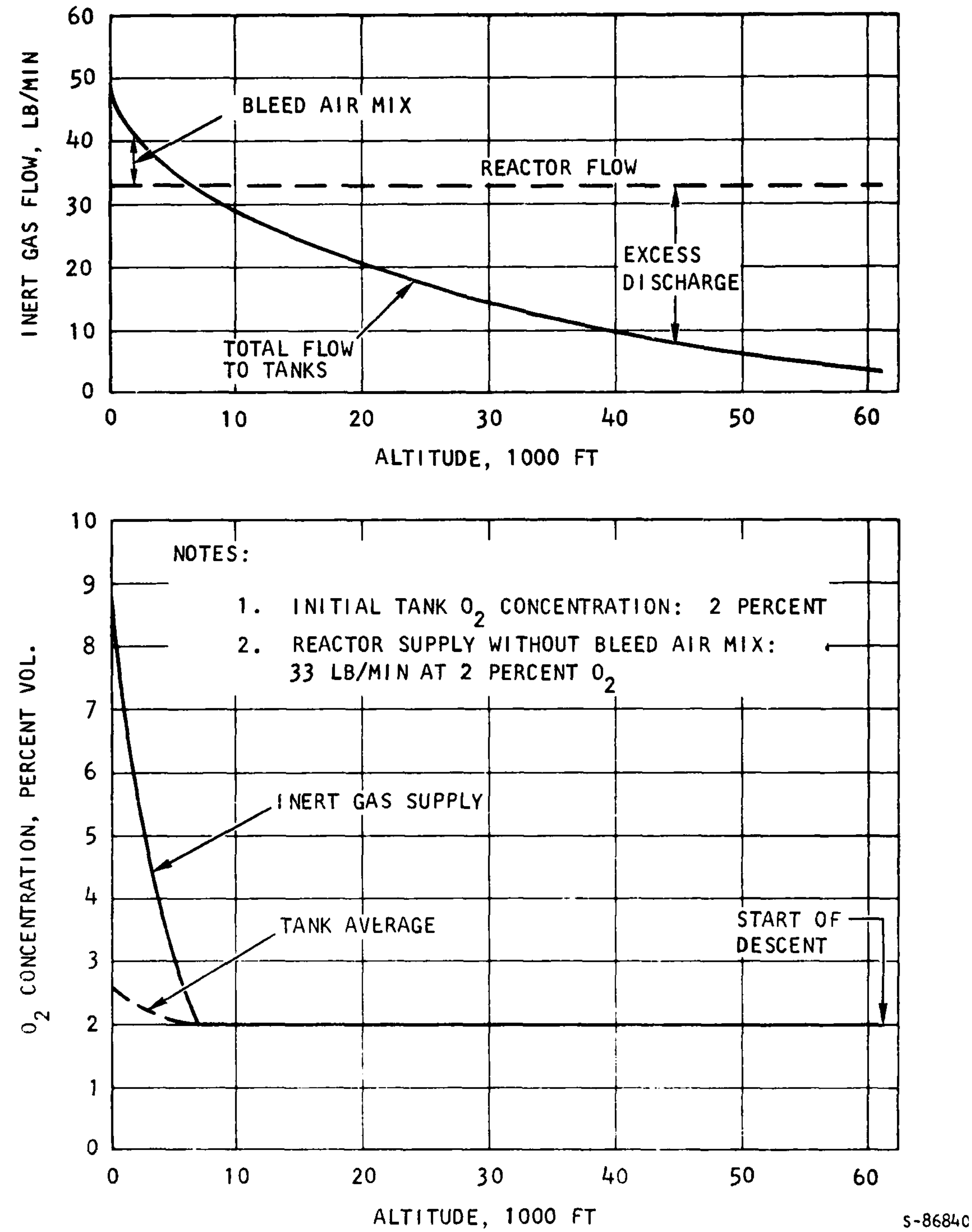


Figure 37. System Flow Characteristics During Maximum Normal Descent

52 lb/min is estimated in terms of product gas O_2 concentration at 4 percent. A slight increase in the size of this unit (from 190 to 210 lb) will provide a 56 lb/min, 4-percent O_2 capability. This low-grade inert gas mixed with 50-lb/min bleed-air will satisfy the 106-lb/min requirements at sea level with a maximum O_2 concentration of 12 percent. This approach represents a 90-lb and 1.9-cu-ft advantage over the Halon 1301 system considered above; it is recommended for this application.

Figure 35 shows the high-flow circuit flow rates and gas composition when used to cover emergency descent conditions. In addition to a slightly larger reactor, the higher flow requirements will require a two-position fuel-air control. This could be done by addition of a second set of nozzles designed to handle the additional flow. In addition, an emergency bleed-air inflow valve is required.

Flow characteristics during emergency descent are plotted in Figure 38. Starting at 39,000 ft with 20-percent fuel remaining in the tanks, the aircraft descent rate is 9,500 ft/sec. The total inert gas flow rate required increases from 25.5 lb/min at 39,000 ft to 106 lb/min at sea level.

At the start of descent, the 33-lb/min unit will be activated in the normal mode. Decaying tank pressure due to the limited capability of the low flow (0.5-lb/min) unit will provide the activation signal. The sequence of operation is as follows:

(1) 39,000 to 33,000 ft--2 percent O_2 inert gas is delivered to the tank; inert gas production exceeds the requirements.

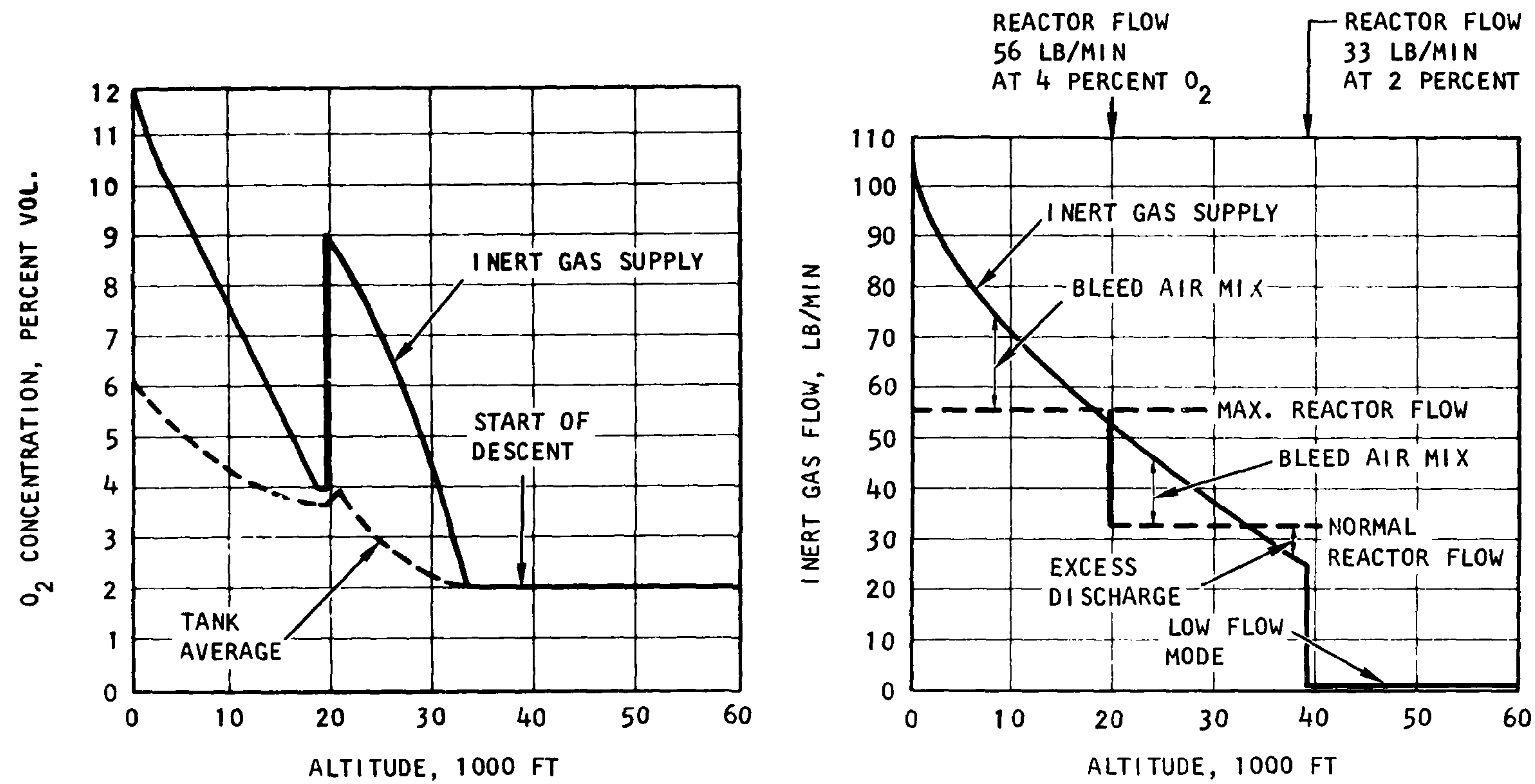
(2) 23,000 to 19,500 ft--The overboard dump valve is closed; bleed air is mixed with the reactor products to the maximum capacity of the bleed-air inflow valve. This corresponds to a 9-percent O_2 inert gas composition. Tank pressure will decay and provide the signal for initiation of the emergency fuel air nozzles at reactor inlet.

(3) 19,500 ft to sea level--Reactor capacity is increased to 56 lb/min--4 percent O_2; bleed air is mixed with the reactor products. When the combined capacity of the reactor and bleed-air control valve is exceeded, the emergency inflow valve opens to allow additional bleed-air flow.

The oxygen concentration of the inert gas supply to the tank is plotted in Figure 38 with the fuel tanks average oxygen content. Although the oxygen concentration of the inert gas supply reaches peaks of 9 and 12 percent, the average oxygen content of the gas in the tanks is only 6.1 percent at the end of the descent.

e. Ram-Air Circuit Design

In the high-flow mode of operation, cooling of the inert gas will be effected primarily in a cooler-condenser using ram air as the heat sink. Under most flight conditions, the ram-air temperature limits achievable



NOTES:

1. INITIAL TANK O_2 CONCENTRATION: 2 PERCENT
2. REACTOR SUPPLY WITHOUT BLEED AIR MIX:
   - 33 LB/MIN AT 2 PERCENT O_2
   - 56 LB/MIN AT 4 PERCENT O_2

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Figure 38. System Flow Characteristics During Emergency Descent

cooling to a level well above the desired level. As a consequence, the inert gas temperature and moisture content at condenser outlet exceed the limits imposed by the specification.

To supplement the condenser, a cooling turbine is incorporated in the system. Expansion of the inert gas from 40 psia to a pressure level of about 18 psia maximum is sufficient to provide a cooling effect of approximately 100°F. Power generated in the turbine is expanded in a ram-air fan. A schematic of the circuit is presented in Figure 39.

A number of parameters must be considered to optimize the design of the condenser-turbine-ram-air circuit. These parameters include turbine outlet temperature, condenser effectiveness, ram-air flow, and ram-air circuit pressure drop.

The turbine cooling effect is determined by the pressure ratio available and the desired turbine outlet temperature. In this case, a maximum turbine pressure ratio of about 2.3 is available. With a desired turbine outlet temperature of 35°F, the condenser must cool the inert gas to approximately 130°F.

Parametric condenser weights are presented in Table XI for a range of ram-to-inert gas flow ratio from 3 to 5:1 and for turbine outlet temperatures 35° and 45°F. The data shows that condenser weight varies only slightly over the range of parameters considered. This is mainly due to the effect of the ejector powered by the high-flow reactor cooling air stream. The unit selected for the system has a ram-to-inert flow ratio of 4:1 with a turbine outlet temperature of 35°F. The reason for the selection is the requirement to minimize the moisture content of the inert gas delivered to the tank.

f. Inert Gas Contaminants

Contaminants in the inert gas stream from the reactor will be primarily from oxidation of the sulfur contained in the fuel and from the water formed in the oxidation reaction.

(1) SO_2 Control

Corrosion tests conducted as part of this program and reported in Section IV have shown the necessity for removal of the SO_2 from the reactor inert gas stream immediately downstream of the reactor to obviate severe corrosion problems in the inerting system itself and also in the aircraft fuel tanks. Preliminary investigations have determined that manganese dioxide (MnO_2) is effective in absorbing SO_2 at temperature levels as high as 900°F.

Jet fuel specifications define a maximum sulfur content of 0.15 percent by weight. An analysis of typical bomber missions reveals that the total quantity of fuel reacted in the low and high flow reactors over a 500-hr period is about 5000 and 270 lb, respectively. Managanese dioxide pellets packed in the inert gas stream passages downstream of the catalyst bed will be used for SO_2 removal.

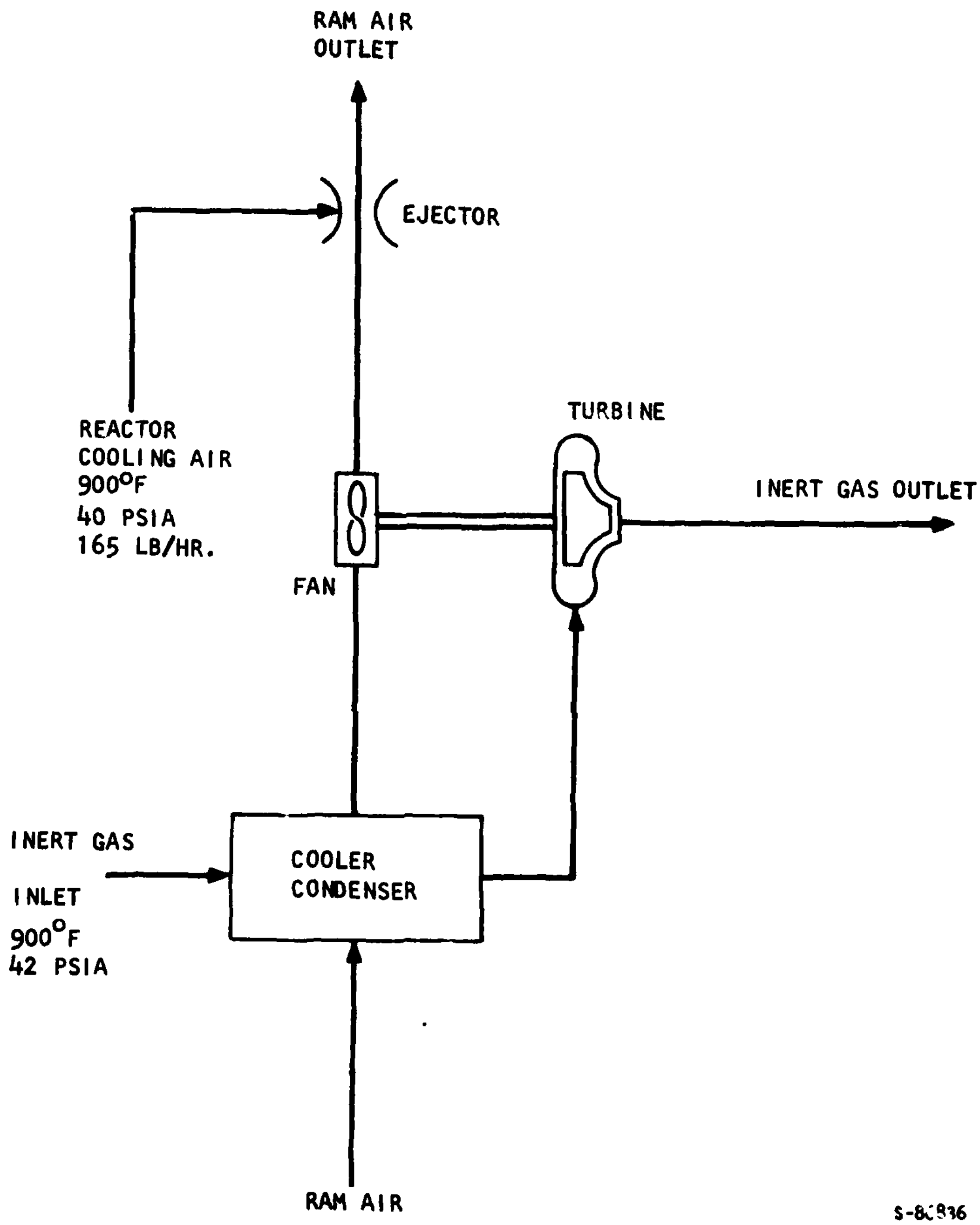


Figure 39. High Flow Cooling Circuit

TABLE XI

PARAMETRIC CONDENSER WEIGHT

Turbine outlet temperature	35°F			45°F		
Ram-to-Inert flow ratio	3:1	4:1	5:1	3:1	4:1	5:1
Ejector ΔP available, psi	2.2	1.6	1.3	2.2	1.6	1.3
Condenser UA required, Btu/hr °F	60	49	45	54	44	39
Condenser weight, lb	13.8	12.6	12.2	12.1	11.1	10.6

About 10-lb manganese dioxide charge can be loaded in the high-flow unit; this will be sufficient for the absorption of 10.5 lb of sulfur dioxide corresponding to an average fuel sulfur content of about half the maximum value specified. Note that additional sorbent could be packed in the reactor outlet manifold if necessary.

(2) Moisture Control

Previous discussions of thermal control have shown that the gas temperature at cooling turbine outlet is controlled at 35°F. This corresponds to a water content of 24 gr/lb dry inert gas at a turbine outlet pressure of 18 psia.

Turbine power is relatively small and since the performance of the ram air fan contributes only a fraction of the power necessary to drive the ram air through the condenser, a turbine outlet pressure control could be incorporated in the system. In this manner condensation would take place at higher pressure. Since most of the inert gas flow input to the tank is during high flow mode operations, the total moisture input to the fuel tank would be kept at a minimum. On the basis of a turbine back-pressure control, estimates of the total water flow to the tanks reveals that 15,500 gr water will be entrained with 534 lb of inert gas over an entire mission. This corresponds to an average moisture content of 26.9 gr/lb inert gas, which is below the maximum value specified (30 gr/lb). Without the back-pressure control, the average moisture content of the inert gas over the same mission is 38.8 gr/lb inert gas. This does not appear excessive although it is slightly higher than the specification value.

2. SYSTEM DESCRIPTION

A schematic of the fuel tank inerting system is presented in Figure 40. The system is designed to meet all the requirements of a typical large bomber mission, including emergency descent. Functionally, the system comprises three modules: (1) inert gas generation module, (2) inert gas conditioning module, and (3) tank pressurization module.

a. Inert Gas Generation Module

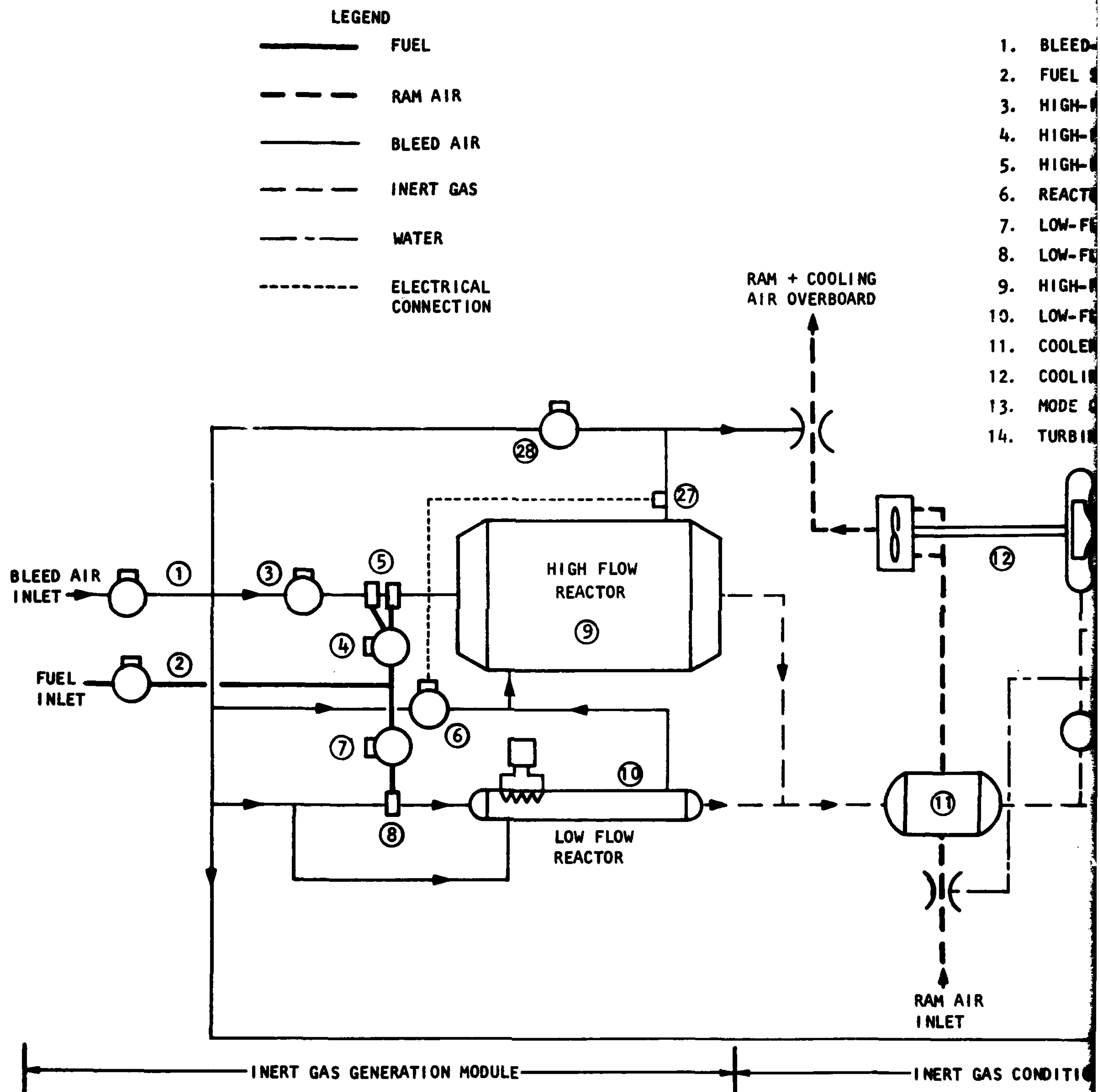
Inert gas is produced by catalyzed oxidation of jet fuel at low temperature. The source of oxygen is bleed air derived from the aircraft bleed air supply conditioned at 45 psia, 450°F nominal. Two reactors are used to satisfy the wide range of inert gas flow requirements of the aircraft. These two reactors operate at constant flow; the low-flow reactor will generate 0.5 lb/min of inert gas continuously throughout the mission. This reactor will satisfy the aircraft fuel tank pressurization requirement for over 90 percent of the mission duration. The high-flow reactor is normally on standby and activated only during the high-flow demand period, sparging, and descent. Capacity is 33 lb/min in normal operation.

Two shutoff valves (items 1 and 2) are used for system isolation. Startup is effected by opening these valves and allowing conditioned bleed air at 450°F to the small flow reactor. Bleed air is used as the process gas within the catalyst bed and also as a source of cooling air. An electrical heater adjacent to the catalyst passages is powered to supplement bleed-air heating and accelerate the startup cycle. When the catalyst bed temperature reaches 600°F, fuel flow is initiated by opening the fuel shutoff valve (item 7). The flow of bleed air and fuel to the catalyst bed is metered by orifices in the low-flow fuel nozzle (item 8). The oxidation reaction will proceed within the single catalyst passage of the reactor. Under steady-state operation, inert gas production, excluding water of reaction, will be 0.5 lb/min. The oxygen concentration of the inert gas will be lower than 1 percent.

Manganese dioxide pellets within the reactor passages and downstream of the catalyst bed will absorb the sulfur dioxide formed as a result of oxidation of the sulfur compounds contained in the fuel.

Catalyst bed pressure is maintained at 45 psia (nominal) The inert gas temperature at reactor outlet is 900°F. This gas is ducted to the conditioning module described later.

Bleed-air metered into the cooling passages of the low-flow reactor will maintain the temperature of the catalyst bed at a maximum value of 1300°F. The cooling bleed air flow at a rate of 2.5 lb/min and a temperature of 900°F is ducted to the cooling passages of the high-flow reactor and exhausted overboard.



LEGEND
FUEL
RAM AIR
BLEED AIR
INERT GAS
WATER
ELECTRICAL CONNECTION
RAM + COOLING AIR OVERBOARD
1. BLEED
2. FUEL
3. HIGH-
4. HIGH-
5. HIGH-
6. REACT
7. LOW-F
8. LOW-F
9. HIGH-
10. LOW-F
11. COOLE
12. COOLI
13. MODE
14. TURBI
BLEED AIR INLET
FUEL INLET
HIGH FLOW REACTOR
LOW FLOW REACTOR
RAM AIR INLET
INERT GAS GENERATION MODULE
INERT GAS CONDITI

B

1. BLEED-AIR SUPPLY SHUTOFF VALVE
2. FUEL SHUTOFF VALVE
3. HIGH-FLOW MODE BLEED SHUTOFF
4. HIGH-FLOW MODE FUEL SHUTOFF VALVE
5. HIGH-FLOW FUEL NOZZLES
6. REACTOR TEMPERATURE CONTROL VALVE
7. LOW-FLOW MODE FUEL SHUTOFF VALVE
8. LOW-FLOW FUEL NOZZLE
9. HIGH-FLOW REACTOR
10. LOW-FLOW REACTOR
11. COOLER-CONDENSER
12. COOLING TURBINE FAN ASSEMBLY
13. MODE CONTROL VALVE
14. TURBINE BYPASS CONTROL
15. WATER SEPARATOR - TURBINE OUTLET
16. HIGH-FLOW DUMP VALVE
17. HIGH-FLOW BLEED MAKEUP
18. EMERGENCY BLEED-AIR INFLOW VALVE
19. TEMPERATURE SENSOR
20. FUEL COOLER
21. FUEL BYPASS VALVE
22. TEMPERATURE SENSOR
23. WATER SEPARATOR
24. LOW-FLOW DUMP VALVE
25. LOW-FLOW BLEED MAKEUP
26. INERT GAS FILTER
27. TEMPERATURE SENSOR
28. BLEED AIR SHUTOFF VALVE

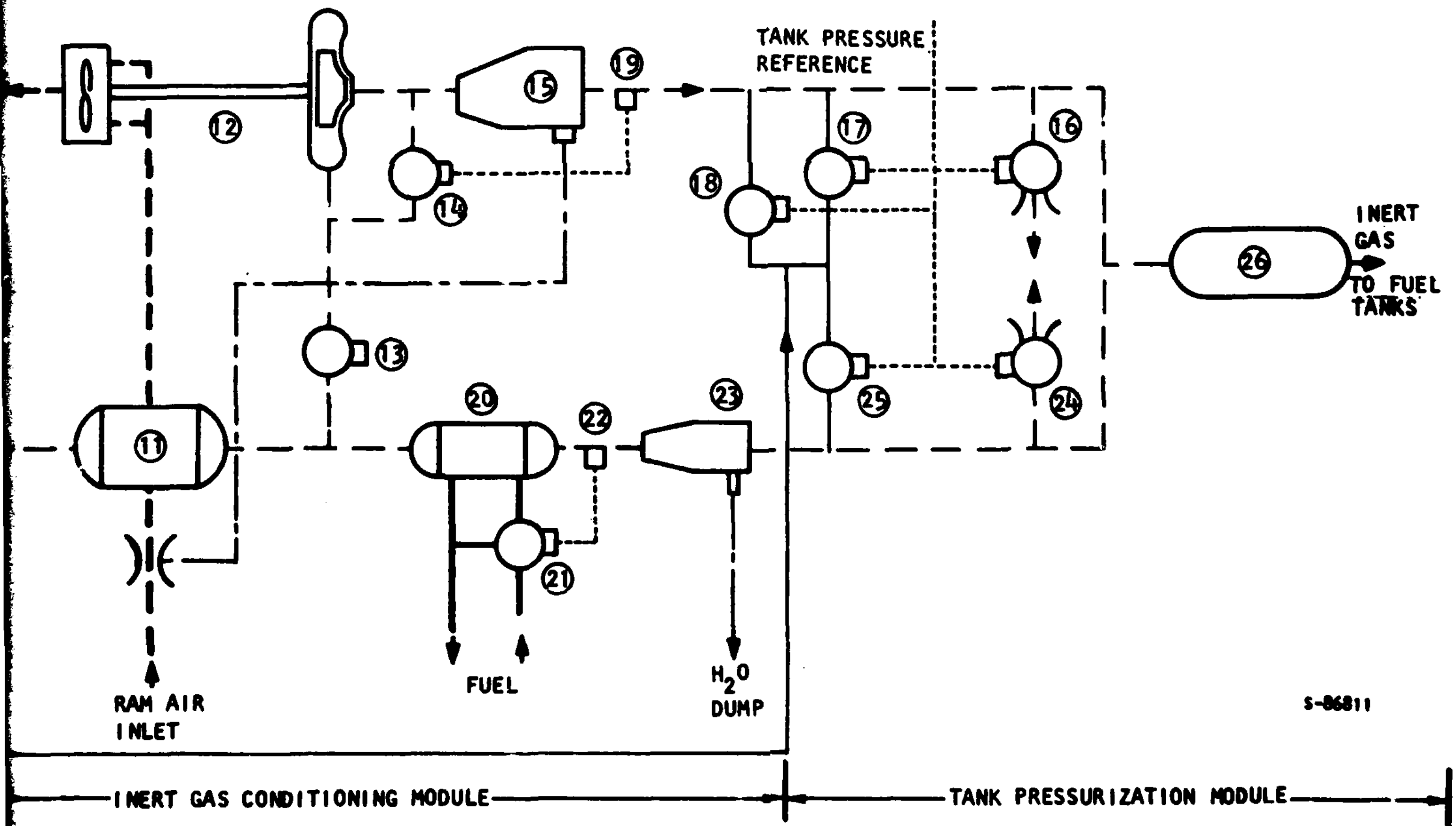


Figure 40. System Schematic

The temperature of the catalyst in the high-flow reactor is maintained above the reaction self-sustaining temperature by the flow of 900°F bleed-air from the low-flow unit. The reactor is activated upon a signal of decreasing fuel tank pressure, indicative that the low flow reactor capacity is insufficient to meet the demand. Startup of the high-flow reactor can also be effected manually by the crew to provide the inert gas flow required for fuel tank sparging. These signals, either automatic or manual, will be used to open the 3-position bleed air and fuel shutoff valves, items 3 and 4, to the NORMAL position. Bleed-air and fuel enter a set of fuel nozzles, item 5, which controls the flow of both fluids to provide stoichiometric conditions at reactor inlet. The oxidation reaction will proceed over the 900°F catalyst bed and steady state operation will be reached within a period of about 1 min. Production of inert gas will be 33 lb/min at a maximum reactor temperature of 1300°F. Oxygen concentration of the product gas stream will be less than 2 percent. Inert gas from the catalyst bed passes through a manganese dioxide sorbent bed within the reactor and is ducted to the conditioning module.

Bleed air at 450°F is used for reactor cooling. In this case, the bleed-air flow is controlled (item 6) to maintain a 900°F temperature at reactor outlet. A thermocouple (item 27) monitors cooling-air outlet temperature and provides the signal for operation of the cooling air flow control valve. The cooling bleed-air is used to power an ejector in the ram air circuit of the conditioning module.

The high-flow reactor capacity is adequate to provide tank pressurization in all normal modes of operation. However, during emergency descent, the inert gas demand exceeds the normal capability of the reactor. As a result, fuel tank pressure will drop. This signal is used to power the high-flow bleed-air and fuel control valve (items 3 and 4) to a third position, EMERGENCY. Fuel and bleed-air will then be admitted to a second set of nozzles upstream of the reactor, thus increasing the reactant supply. Under these conditions, inert production will increase from 33 to 56 lb/min. Reactor effectiveness, however, will drop; the inert gas oxygen concentration will increase from 2.0 to 4 percent. Reactor cooling will be adjusted automatically to maintain a 900°F cooling air outlet temperature.

b. Inert Gas Conditioning Module

In this module, inert gas produced in the reactor is cooled and dried prior to delivery to the fuel tanks. A single condenser (item 11) is used to cool reactor gases in both the low- and high-flow modes of operation. Downstream of the condenser a shutoff valve (item 13) is closed during low-flow mode of operation. In this case, a fuel cooler provides additional conditioning capability when required. In the high-flow mode, reactor gases from the condenser are expanded in a turbine for supplemental cooling and moisture removal.

(1) Low-Flow Mode

Inert gas is ducted to the cooler-condenser (item 11) where it is cooled by ram air. In this mode of operation, only ram pressure is available to assure cooling air flow through the unit. However, because of the very low loads due to the low inert gas flow, this flow of ram air will be sufficient to cool and dehumidify the inert gas in most flight conditions. During ground operations ram air flow through the cooler-condenser is induced using bleed air to power the ram air ejector. A solenoid bleed-air shutoff valve (item 28) is provided for this purpose. This valve is opened only during low-flow mode of operation on the ground and is shut when the high-flow reactor is activated.

Condensate collected in the cooler-condenser is injected in the ram air circuit upstream of the unit to enhance the heat sink potential of the ram air.

Under certain hot-day ground operations and under high Mach no cruise conditions, the temperature of the ram-air is too high for adequate cooling of the inert gas. Maximum ram-air temperatures under high speed cruise can be as high as 350°F. Under such conditions further inert gas cooling is effected using fuel as the heat sink. The fuel cooler (item 20) will control the inert gas at a temperature of 100°F. A bypass valve (item 21) adjusts the flow of fuel through the cooler to maintain this temperature. A centrifugal water separator (item 23) collects condensate formed in the fuel cooler and dumps this relatively small quantity of water overboard.

The quantity of water entrained to the fuel tanks through this circuit is relatively small. Generally, the effectiveness of the condenser under conditions of very low flow will be high and the inert gas temperature at condenser outlet will approach that of the ram air. Estimates made of the water content of the inert gas under low flow conditions show that less than 30 gr of water/lb of dry inert gas will be delivered to the fuel tanks from that circuit.

The flow through the fuel-cooler is continuous throughout the mission and controlled by an orifice downstream of the separator.

(2) High-Flow Mode

When high gas flows are required to meet tank pressurization demand, the mode control valve (item 13) will open at the same time as the high-flow reactor shutoff valves. The major portion of the condenser flow will be directed to the cooling turbine (item 12) where the inert gas will be cooled and further dehumidified by expansion. The turbine is loaded by a fan in the ram-air circuit.

The ram-air circuit pressure drops are made up by (1) the ram pressure, (2) the fan driven by the expansion turbine, and (3) the ejector powered by hot cooling air from the high-flow reactor. The condenser is designed to provide

an inert gas temperature at outlet of 130°F with a ram-air flow of 130 lb/min. Moisture condensed in the unit is collected and evaporated in the inlet ram air stream to depress the temperature of the ram air and enhance its thermal capacity. At ram-air temperatures below freezing, condensate will be dumped overboard directly.

The cooling turbine is designed to provide a 35°F inert gas temperature with a pressure ratio of 2.2 and a flow rate of 33 lb/min. A bypass control valve (item14) controls the flow of inert gas to the turbine to assure against water freezing downstream of the turbine. This control valve is positioned according to a signal from a temperature sensor (item 19) located downstream of the water separator.

Condensate formed in the expansion process is collected in a static swirl phase separator (item 15). Water from the separator is injected into the condenser cooling air stream.

c. Tank Pressurization Module

Two parallel pressurization modules are used to permit operation over the wide flow range. In the low-flow mode of operation, tank pressure is maintained by bleed makeup and inert flow dumping. When inert gas is produced in excess of tank demand, the excess is dumped overboard through a pressure relief valve (item 24) referenced to tank pressure. This signal is also used to mix bleed air with the inert gas from the low-flow condition ing section. A pressure regulator, item 25, meters the bleed air into the inert gas. This valve is orificed so that the maximum oxygen concentration of inert-bleed-air mixture to the fuel tank does not exceed 9 percent. Figure 35 shows the flows and concentrations through the circuit under this mode of operation.

In the high-flow mode of operation, control is effected in the same manner with the dump valve (item 16) and the bleed makeup valve (item 17). Again the bleed makeup valve is sized to limit the flow of bleed-air into the inert gas stream. The maximum oxygen concentration of inert-bleed is limited to 9 percent. Figure 35 depicts the system flow during maximum flow conditions and illustrates the operation of the pressurization module.

A second bleed-air makeup valve (item 18) is provided in parallel with item 17. This valve is set to operate at a lower setting than the normal bleed air valve and will only be used in emergency when the inlet gas oxygen concentration is allowed to reach 12 percent. Flow characteristics through the system are shown in Figure 35.

A filter (item 26) protects the fuel tanks from solids which could be entrained by the inert gas stream.

3. EQUIPMENT SUMMARY

The characteristics of the components shown in the schematic of Figure 40 are presented in Table XII. The function of each component is defined and design data are given. The system incorporates 28 components-assemblies. With the exception of the catalytic reactor, all equipment listed represents state-of-the-art hardware.

The reactors, although very different in size, use the same modular construction. Each module is almost identical to that of the prototype module described in Section III. Differences involve material gages, particularly a considerable reduction in the thickness of the plates separating the finned passages of the unit.

The weights listed in Table XII are considered accurate since the equipment listed is, in general, comparable to existing off-the-shelf equipment widely used in commercial and military aircraft systems. The reactor weight, which by far overshadows that of any other component listed, was scaled from the actual weight of the prototype module. Scaling involved changes in plate thickness as mentioned above and sizing the unit for the inert gas flow required by addition of identical modules. Reactor weight is believed to be an accurate estimate of a flight configured unit.

4. OVERALL SYSTEM CHARACTERISTICS

A summary of the overall system characteristics is presented in Table XIII. Specification data are also listed for comparison. With respect to system performance, adequate design data was made available through the prototype module test program for accurate prediction of the flight system performance. In all cases, including emergency descent, the predicted performance matches or exeeds the requirements.

At this time, system life and maintenance intervals can only be used as a design goal. Sufficient life data on the catalyst is not available. Further testing is required to ascertain the 500-hr goal, although long life has been reported by the catalyst manufacturer for the kind of duty cycle involved in operation of the inerting system.

Limited life system components include the filter (item 26, Table XII) and the two reactors. Although the largest portion of the inert gas produced is through the high-flow reactor, the large unit duty cycle represents only a fraction of the total mission. For a typical mission, the low-flow unit will be active at all times. The large unit will be active only for sparge and descent. Both reactors use the same basic module. The small unit has 1 module and the large one, 35; specific inert gas production rates per module are 0.5 lb/min/module and 0.94 lb/min/module, respectively. It follows that if the replacement period for the small reactor is 500 mission hours, the large reactor will have an estimated life extending over 7500 hours.

TABLE XII

COMPONENT SUMMARY

Item	Description	Weight, lb	Function	Design Data
1	Bleed-air supply shutoff valve	5.0	System isolation valve. 45 psig, 450°F supply.	4 in. dia. line, solenoid operated butterfly, on-off.
2	Fuel shutoff valve	0.5	System isolation valve.	Solenoid actuated on-off shutoff valve.
3	High-flow mode bleed shutoff	3.5	Controls the flow of bleed air to the high flow fuel nozzle. Valve is sized for 33/lb/min in normal position and 56 lb/min for emergency descent. Tank pressure signal used to position valve.	2 in. dia. line, solenoid operated 3-position valve: OFF-NORMAL-EMERGENCY.
4	High-flow mode fuel shutoff valve	1.1	Controls flow of fuel to the high flow reactor. Valve is sized to supply two sets of nozzles. In normal high flow mode one set of nozzles is pressurized, in emergency mode both sets are pressurized. Tank pressure signal used to position valve.	Solenoid operated 3-position valve: OFF-NORMAL-EMERGENCY.
5	High-flow fuel nozzles	0.3	Incorporates two sets of nozzles sized for constant fuel flows of 2.24 lb/min and 1.56 lb/min. (Total: 3.8 lb/min)	Standard commercial parts.
6	Reactor temperature control valve	4.5	Maintains high flow reactor cooling air temperature at outlet of 900°F. Valve is sized for normal air flow of 165 lb/min providing cooling-to-inert air ratio of 5:1. Maximum valve flow during emergency descent is 280 lb/min.	3 in. dia. line, electropneumatic pilot operated butterfly valve. Actuating signal is temperature at reactor outlet.
7	Low-flow mode fuel shutoff valve	0.5	Controls (on-off) flow of fuel to the low flow reactor fuel nozzles.	ON-OFF solenoid operated valve.
8	Low-flow fuel nozzle	0.2	Atomizes constant flow of fuel (0.034 lb/min) in the bleed air stream (0.5 lb/min) to the low flow reactor.	Standard commercial part.
9	High-flow reactor	210	Designed for low temperature catalytic oxidation of stoichiometric mixtures of bleed air and jet fuel. Normal bleed air flow rate is 33 lb/min (constant); oxygen content of process gas at outlet is 3% (nominal). Maximum flow of bleed air is 56 lb/min (constant) during emergency descent; oxygen content of bleed air is then 4% (nominal). Catalyst is American Cyanamid Aero-Ban AC. Reactor contains 10 lb of MnO_2 in outlet passages for absorption of SO_2 produced in fuel oxidation reaction. Reactor is maintained at temperature above self-supporting temperature of Aero-Ban AC catalyst throughout the flight. Cooling during operation is with bleed air at an inlet temperature of 450°F. Cooling air flow is controlled to maintain a 900°F temperature at outlet.	Reactor construction is a parallel flow plate fin heat exchanger. Alternate finned passages are filled with catalyst over which oxidation reaction takes place. Total catalyst volume is 595 $in.^3$ in 35 passages 0.25 in. high by 5.85 in. wide and 11.61 in. long. MnO_2 in pellet form is loaded in the same passages downstream of the catalyst. Cooling air passages on each side of the catalyst passages maintain metal temperature below 1300°F at any point in reactor. Cooling air flow is approximately 5 times air flow. Reactor details are same as for prototype module depicted in Figure 29; the number of catalyst passages is 35 and construction is for flight weight design.
10	Low-flow reactor	8.8	Generates a constant flow of inert gas (0.5 lb/min) at an oxygen concentration of 1% nominal. This flow is adequate for all mission modes except for tank sparging and descent. Cooling is with bleed air at a nominal flow of 2.5 lb/min.	Similar to high flow reactor except design incorporates only 1 catalyst passage sandwiched between two cooling air passages. An electrical heater adjacent to the catalyst bed provides the temperature levels (600°F) necessary for start up.
11	Cooler-condenser	12.6	Product gases from the reactors are cooled in this unit. Ram air constitutes the heat sink. Ram air flow is assured by a turbine driven fan during high flow mode. During low flow mode ram-to-ambient ΔP is adequate to cool the 0.5 lb/min reactor outlet. Condensate formed in the unit is collected and injected in the ram air stream to enhance cooling capacity. Inert gas temperature at unit inlet is 900°F. In the high flow mode (33 lb/min) the unit is designed to provide at 200°F temperature at outlet. In the low flow mode (0.5 lb/min) outlet temperature will be near ram air.	Stainless steel plate fin unit of conventional construction. Flow configuration is crossflow.
12	Cooling turbine fan assembly	15.0	Cooling turbine used in high flow mode to control the inert gas temperature delivered to fuel tanks at 35°F. Condensate formed during expansion is separated downstream. Turbine power is used to drive a fan in the ram air circuit during all high flow mode conditions including sea level static and high altitude low Mach number.	Radial inflow, axial outflow expansion turbine coupled to a radial flow fan. Turbine is sized to handle 33 lb/min of 40 psia inert gas at a pressure ratio of 2.2. Fan flow at sea level is 132 lb/min with a fan pressure rise of 1.1 psi. The turbine-fan assembly is of aluminum construction.

TABLE XII (cont)

Item	Description	Weight, lb	Function	Design Data
13	Mode control valve	3.0	Controls the flow of inert gas to the cooling turbine. Valve is opened upon a signal from tank pressure.	Similar to item 3 except has only two positions: ON-OFF.
14	Turbine bypass control	2.7	Controls the flow of inert gas through the cooling turbine to maintain a temperature of 35°F downstream of the water separator, thus preventing condensate freezing. The valve is operated from a signal from item 19, temperature sensor.	Electropneumatic pilot operated valve.
15	Water separator - turbine outlet	4.1	Condensate formed in the expansion turbine is separated in a swirl type separator. This water is sprayed into the ram air upstream of the cooler-condenser (item 11) to enhance cooling capacity.	Separator is a static device fabricated of aluminum. Within the unit air is swirled tangentially and liquid water separated by centrifugal force is collected on a coalescer.
16	High-flow dump valve	2.0	Controls flow of inert gas to the fuel tank to maintain tank pressure of 1.5 psig. Control is effected by dumping overboard the excess inert gas capacity from the high flow reactor which operates at a constant flow of 33 lb/min (56 lb/min during emergency descent).	High flow, low pressure relief valve available ΔP of 1.5 psi of upstream pressure of 2.5 psia maximum flow: 56 lb/min. Construction similar to aircraft cabin pressure control valves.
17	High-flow bleed makeup	4.0	Valve opens to supplement inert gas generated in the reactor to maintain fuel tank pressure at 1.5 psig when tank demand exceeds 33 lb/min. Valve is orificed to limit bleed air flow to 19 lb/min corresponding to a maximum oxygen concentration of 9% in the inert gas delivered to the tanks.	Pressure regulating valve. Maximum flow is 19 lb/min with a 45 psia, 450°F inlet. Maximum downstream pressure is 20 psia.
18	Emergency bleed-air inflow valve	4.0	Valve opens to allow bleed air flow into the inert gas stream under emergency conditions only. When tank flow demand exceeds reactor production (56 lb/min) and high flow bleed make up (19 lb/min) valve is orificed to limit bleed flow to 31 lb/min corresponding to a 12% oxygen concentration in the inert gas feed to the fuel tanks.	Pressure regulating valve. Maximum flow is 31 lb/min with a 45 psia 450°F inlet. Maximum downstream pressure is 20 psia. Similar to item 17 except for higher maximum flow and slightly lower tank pressure regulation.
19	Temperature sensor	0.4	Monitors inert gas temperature at high flow separator outlet and provides signal for operation of the turbine bypass control valve (item 14).	Standard commercial equipment.
20	Fuel cooler	1.3	Used to supplement condenser heat rejection capability under conditions of high ram air temperatures. Unit used only to process 0.5 lb/min of inert gas. Fuel flow through the heat exchanger is controlled to maintain inert gas temperature of 100°F at outlet.	Tubular unit of aluminum construction.
21	Fuel bypass valve	1.1	Controls the flow of fuel through the fuel cooler to maintain a 100°F inert gas temperature at outlet. Item 22, temperature sensor provides the signal for valve actuation.	Motor actuated flow control valve.
22	Temperature sensor	0.4	Monitors inert gas temperature at fuel cooler outlet and provides signal for actuation of fuel bypass valve (item 21).	Similar to item 19 above.
23	Water separator	0.8	Separates and collects condensate formed in the fuel cooler (item 2[illegible]). Unit designed to handle 0.5 lb/min of inert gas. Water is dumped overboard.	Similar to item 15 above, unit designed for 0.5 lb/min.
24	Low-flow dump valve	1.0	Dumps excess inert gas overboard when low flow reactor constant capacity (0.5 lb/min) exceeds fuel tank demand (0 minimum). Tank pressure provides the control signal.	Pressure relief valve, max flow capacity is 0.5 lb/min, inlet pressure of 4.0 psia.
25	Low-flow bleed makeup	1.3	Supplements low flow reactor when tank demand exceeds 0.5 lb/min. Flow is limited to 0.3 lb/min to maintain a maximum oxygen concentration of 9% in the inert gas delivered to the fuel tanks.	Pressure regulating valve. Maximum flow is 0.3 lb/min at inlet of 45 psia and 450°F. Maximum downstream pressure is 20 psia.
26	Inert gas filter	4.0	Prevents tank contamination with solids from the system.	Radial flow fiberglass unit.
27	Temperature Sensor	0.4	Monitors cooling air temperature at high flow reactor outlet and provides signal to temperature control valve, item 6, for cooling air flow control.	Similar to item 19 above.

TABLE XIII

COMPARISON OF SPECIFIED AND PREDICTED CHARACTERISTICS

Parameter	Specification Requirements	Estimated Characteristics
Ambient Pressure, psia	1.0 - 14.7	1.0 - 14.7
Tank Pressure, psig	1.5	1.25 - 1.6
Inert Gas Flow, lb/min		
• Normal	0 - 52	0 - 52
• Emergency descent	106 (max.)	106 (max.)
Inert Gas O_2 Concentration, percent vol		
• Normal (including sparging)	2 - 5	1.0 - 2.0
• Maximum normal descent	9	9
• Emergency descent max.	12	12
Inert Gas Moisture Content, gr/lb	30	27
Inert Gas Temperature, $^{\circ}F$		
• Normal	100	100 (max.)
• Max. normal descent	200	180
• Emergency descent	325	230
Controls		
• Normal	Automatic	Automatic
• Sparging	Manual	Manual
Life, hr	4000	4000 (design)
Maintenance Period, hr	500	500 (design)
Weight, lb	780 (max.) 416 (goal)	305 (including emergency descent)

System controls are completely automatic, except for startup and sparging. Startup requires the crew to activate open the system isolation valve and to switch on the fuel control valve to the small reactor. This last operation could be made automatic using reactor temperature measurement to signal the fuel control valve open. Ground operation with the small reactor will require bleed-air flow to power the ram-air ejector. Again, operation of the bleed-air valve could be automated. This would require sensing the temperature at condenser outlet or sensing the flow of ram-air through the condenser.

The estimated system weight is 305 lb, including structures and ducting internal to the system. It is important to note that the system is designed to meet the emergency descent requirements. The weight added to the system to provide this capability is 26 lb.

5. EQUIPMENT ARRANGEMENT

A package drawing of the system is presented in Figure 41. This package was prepared without consideration of aircraft interface constraints that define maximum envelope dimensions and duct interfaces. As a result, the overall size of the package is about minimum because the ducts (ram-air, bleed-air inlet and inert gas outlet) were located conveniently with respect to component arrangement. The arrangement was developed to provide (1) high equipment density, (2) low duct pressure drops, and (3) accessibility for ease of maintenance.

As shown in Figure 41, the components were located to minimize the length and number of bends in the large ducts. The ram air enters the package at the cooler-condenser; an interface duct, not shown, of approximately 6-in.-dia or equivalent will be necessary to handle the high flow. The ram-air fan inlet plenum is mounted directly on the cooler-condenser outlet manifold. The ram air is exhausted from the side of the package. The ejector downstream of the fan is not shown.

Bleed air enters the system from the side through a 4-in.-dia duct. From that duct, the bleed air is distributed through the package to provide all functions defined previously. Generally, the package is arranged to provide through-flow of bleed air in the high-flow mode. The reactor product gases are ducted directly into the cooler-condenser (item 11). Then, the inert gas duct is bent through 180 deg to the turbine inlet scroll. From the turbine outlet, the inert gas flows back through the separator (item 15), the pressurization module, and the filter (item 26) prior to delivery.

The high-flow reactor is the largest and heaviest component of the system. It is located at the bottom of the package; smaller equipment is located above it. The valve module, shown as a block, includes the fuel tank pressurization module (items 15, 16, 17, 24 and 25), the system fuel shutoff valve (item 2), and the fuel cooler bypass valve (item 21).

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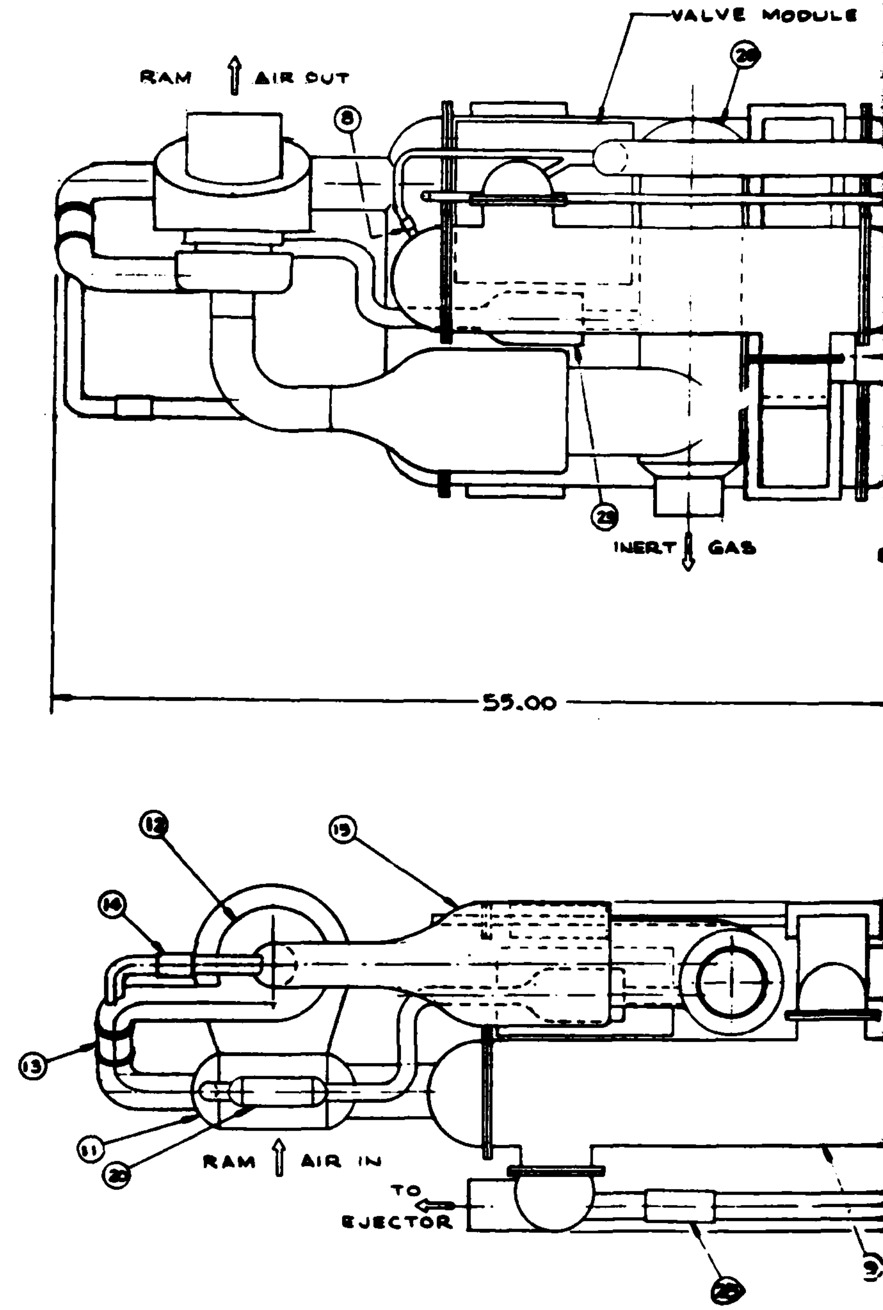
A

1. BLEED-AIR SUPPLY SHUTOFF VALVE
2. FUEL SHUTOFF VALVE
3. HIGH-FLOW MODE BLEED SHUTOFF
4. HIGH-FLOW MODE FUEL SHUTOFF VALVE
5. HIGH-FLOW FUEL NOZZLES
6. REACTOR TEMPERATURE CONTROL VALVE
7. LOW-FLOW MODE FUEL SHUTOFF VALVE
8. LOW-FLOW FUEL NOZZLE
9. HIGH-FLOW REACTOR
10. LOW-FLOW REACTOR
11. COOLER-CONDENSER
12. COOLING TURBINE FAN ASSEMBLY
13. MODE CONTROL VALVE
14. TURBINE BYPASS CONTROL
15. WATER SEPARATOR - TURBINE OUTLET
16. HIGH-FLOW DUMP VALVE
17. HIGH-FLOW BLEED MAKEUP
18. EMERGENCY BLEED-AIR INFLOW VALVE
19. TEMPERATURE SENSOR
20. FUEL COOLER
21. FUEL BYPASS VALVE
22. TEMPERATURE SENSOR
23. WATER SEPARATOR
24. LOW-FLOW DUMP VALVE
25. LOW-FLOW BLEED MAKEUP
26. INERT GAS FILTER
27. TEMPERATURE SENSOR
28. BLEED AIR SHUTOFF VALVE



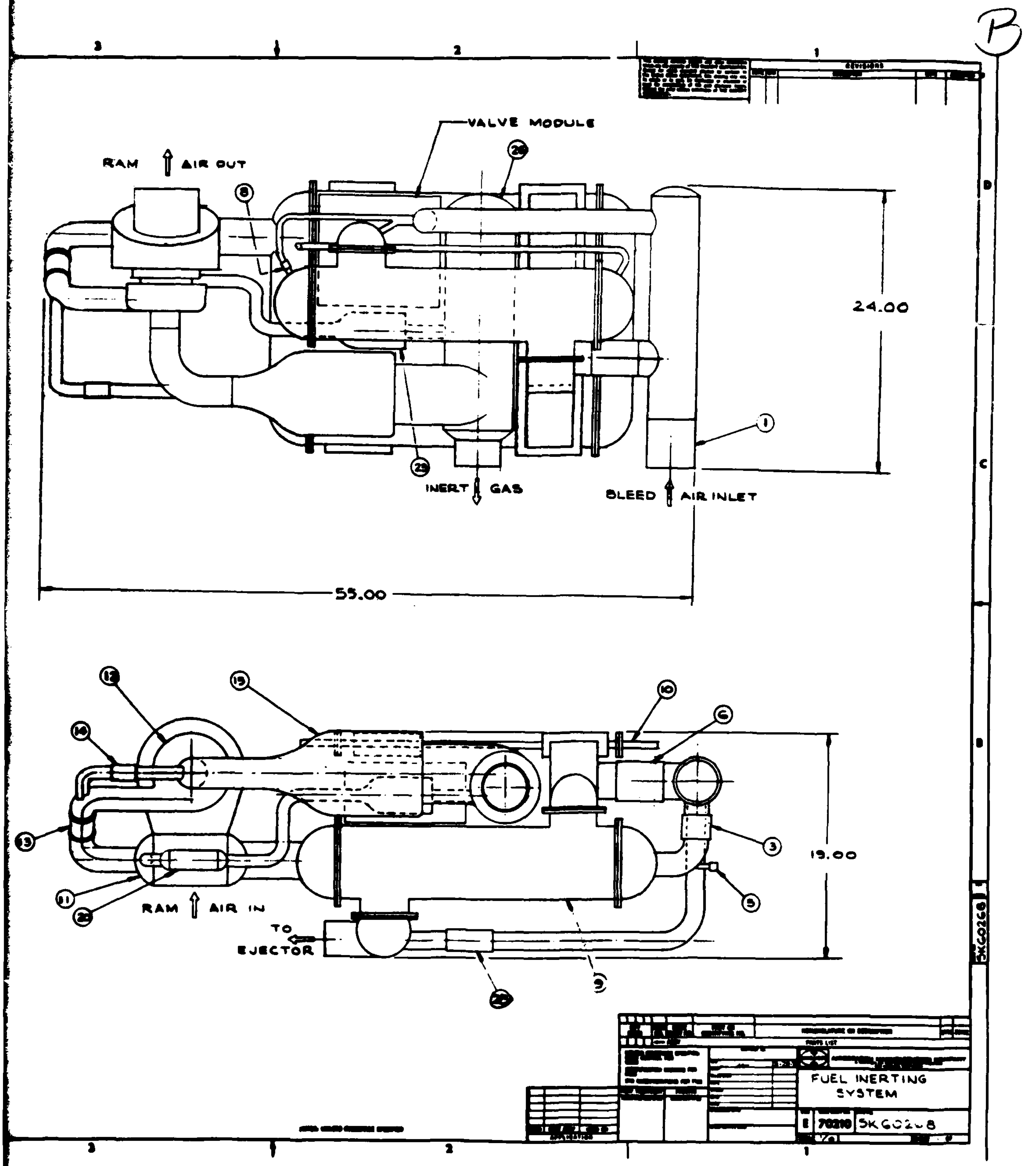


Figure 41. Equipment Arrangement

The low-flow reactor is located on top of the package so that the coolant flow from this unit is ducted directly into the cooling air manifold of the large unit. This minimizes pressure drop and reduces line lengths to a minimum. The coolant flow from the large unit is exhausted near the ram-air duct and can be routed directly to the ram-air ejector (not shown).

The fan-turbine assembly is located at the end of the package and is easily accessible for removal. This location is also optimum in terms of system ram and inert gas ducting.

The low-flow reactor is mounted on top of the package; an optimum location for servicing. The filter (item 26) is easily removable from the side of the unit.

In preparing the package, attention was paid to component support. Most of the equipment will be mounted on a structure supported by the high flow reactor. The overall package structure is not shown. In all cases, allowances were made to permit insulation of the hot components.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. OVERALL CONCLUSIONS

The program described in this document represents a major milestone in the development of a flight fuel tank inerting system for aircraft applications. The overall achievements of the program can be stated simply, as follows:

a. A prototype catalytic reactor of flight configuration was successfully developed. Very high fuel conversion effectiveness was obtained at stoichiometric fuel-air ratio; the oxygen content of the inert gas was measured repeatedly between 0.5 and 1 percent (vol) at the design flow rate of 1 lb/min.

b. A complete fuel tank inerting system meeting all the requirements of a typical large bomber, including emergency descent, can be built within an envelope of 19 by 24 by 55 in. The weight of this system is estimated at 305 lb.

The conclusions derived from the developmental and analytical program tasks are listed below as they relate to reactor development and system design.

a. Reactor Development

Stable and effective operation of a flight-configured reactor was made possible only through extensive development testing of a number of designs and modifications. Process, hardware, and operational problems were resolved through evolutionary steps which resulted in the design of the prototype module reactor. This reactor design was eminently successful and provided the vehicle for the generation parametric performance data. As a result of the overall test program, the following conclusions were reached concerning reactor and system design and operation.

(1) Catalyst

The American Cyanamid Code A catalyst will promote effective jet fuel oxidation when operated under suitable conditions. This confirms the findings of previous studies.

(2) Reactor Effectiveness

Inert gas oxygen concentrations of 0.5 percent were achieved at 1300°F reactor peak temperature and space velocities on the order of 25,000 hr^{-1}. Under these conditions, fuel oxidation to CO_2 and water was very effective as evidenced by the results of gas analyses.

(3) Fuel-Air Ratio

Operation at near-stoichiometric fuel-air ratio is essential for the generation of a clean, inert gas product with minimum tars and varnishes.

(4) Reaction Stability

A cooled flame arrestor upstream of the catalyst bed is necessary to contain the reaction. Stable operation through recirculation of inert gas is not recommended.

(5) Thermal Control

The major portion of the exothermic heat of reaction is released within a few inches in the longitudinal direction of the reactor--high density heat transfer surfaces are necessary in this area to minimize thermal gradients and peak temperature.

(6) Cooling Flow Pattern

Parallel flow of cooling and bleed air is more effective than counterflow--peak temperatures are reduced and overall catalyst bed temperature is higher.

(7) Cooling Air Source

The high heat transfer rates necessary for thermal control result in cooling stream high-pressure drops. As a consequence, the use of low-pressure ram air for cooling purposes presents some difficulties. Bleed air is recommended.

(8) Reactor Construction

The basic reactor construction represented by the prototype module is very effective in terms of thermal control and also in terms of mechanical design.

(9) Reactor Startup

The use of platinum catalyst for reactor startup is not recommended. Preheating the Code A catalyst to temperatures of 600° to 700°F is a better technique. Preheating could be done with hot air, electrical heaters, or both.

(10) SO_2 Sorbent Bed

The pH of the condensate from the reactor outlet stream was found to be as low as 2.85. A SO_2 sorbent bed at reactor outlet is necessary to prevent system and fuel tank corrosion. Manganese dioxide is tentatively recommended for this purpose.

(11) Tank Materials of Construction

Corrosion testing of tank materials has shown that coatings will be necessary to prevent corrosion damage to most construction materials except titanium. Current coating and sealant materials properly applied will provide adequate protection from the acidic products (SO_2) emanating from the catalytic reactor.

(12) Tars and Varnishes

These products are formed in the reactor as a result of fuel polymerization. The formation rate of these products appears to be directly related to the presence of excess oxygen due to rich fuel-air mixtures or reaction inefficiencies. Under conditions corresponding to effective reactor operation, these products are removed from the system with the condensed water. No accumulation of tars and varnishes on the condenser surfaces was noticed.

b. Flight System

The most important program achievement is the successful operation of a high-effectiveness, inert gas generation reactor in conditions representative of aircraft installation. Generation of parametric performance data and verification of reactor design features made possible the synthesis of a realistic flight system arrangement and the accurate prediction of its performance, weight, and size. Overall system characteristics are estimated as follows:

- Specification requirements--equaled or exceeded in all cases.
- Performance--meets inert gas requirements of a large bomber aircraft over the entire flight envelope, including emergency descent.
- Overall system weight--305 lb, including internal ducting and structure.
- Envelope--19 by 24 by 55 in.

2. RECOMMENDATIONS

In view of the very low system weight (305 lb) estimated for an inerting system meeting all the requirements of a typical high performance military bomber, and considering that the present program has gone a long way toward eliminating development risks, it is recommended that future efforts be aimed at the design and development of a flight prototype system.

To obviate problems at the system level, limited process and component development should be conducted to determine catalyst life and generate design data for a SO_2 sorbent bed.